After peer reviews, published in the *Proceedings of the Space Technology and Applications International Forum (STAIF-2007),* edited by M. S. El-Genk, American Institute of Physics, Melville, New York **880**, pp, 1083-1091, Feb. 12-15, 2007, Paper 012

Reviewer's Comments

Your paper was submitted for peer review. Below are the reviewer's comments, provided for your information. Reviewer's names have been omitted:

Reviewer's Comments on Log No. 012

Reviewer #1:

Fourth line in the Abstract, Gravity should be Gravitational

Fifth line in the Abstract, RF should be Radio Frequency (RF)

Keywords gravity should be gravitational

Fifth line in **HFGW BACKGROUND,** (Baker, 2006) should include another reference in the usual peer-reviewed literature (Baker, 2006a; Baker 2006b). The reference to be added is:

Baker, R. M. L., Jr., "Novel formulation of the quadrupole equation for potential stellar gravitational-wave power estimation," *Astronomische Nachrichten / Astronomical Notes* **327,** No. 7 , pp. 710-713 (2006b).

In the text the STAIF style is Eq. ( ) not equation [ ] and Fig. not figure except at the beginning of a sentence

Second line under Eq. (2), HFGW should be replaced by HFGWs (100 kHz to greater than 100 THz)

Line just above Fig. 1 should read "... shown in Fig. 1, where their latitude and longitude are given in parentheses."

Last line of the paragraph under Fig. 1 should read "HFGWs will propagate through the Earth with little modification, However, please see Baker (2007) for the possible modification of HFGW phase."

The paragraph under the subsection **The Impact of Phase Noise ...**presents some acronyms that are defined in a section at the end of the paper except for 8PSK and 16-PSK. These should be added to the list and a comment inserted here to the effect that the acronyms are defined in a **NOMENCLATURE** Table at the paper's end.

In the next subsection there are some acronym definitions after the acronym is used. Should be fixed.

Forth line above Table 1, QoS should be defined here and in the **NOMENCLATURE**

In the **NOMENCLATURE** should read GW = Gravitational Wave and HFGW = High-Frequency Gravitational Wave

I have already suggested that reference Baker 2006 be 2006a and add a Baker 2006b

This paper is a significant contribution to the communications applications of HFGWs and should be published.

Reviewer #2:

Page 3: Need better rrect bullet alignment.

Page 4: "... check each possibly phase possibility..." Do you mean "possible phase..."?

Page 5, Eq. 5: Split "guardband" into two words as in the rest of the text.

Page 6, Tbls 1 and 2: Split words that are marked by spellcheck.

Page 7: What exactly is a pop? Perhaps a one-sentence definition here would be helpful.

General: Capitalize the word "figure" when referring to a figure in sentences - 'Figure 4' instead of 'figure 4'.

Would there be any biological effects from HFGW's so close to your head when using and HFGW cellphone?

Reviewer #3:

The authors have applied a simple discounted cash flow analysis to the value of a HFGW frequency time standard system. they calculate the time value of money at 10% and IF their assumptions are right re: the cost of the build out; the subscriber rate; the efficiency of the enhancements to the existing telecommunications system and IF the current cost of the existing telecommunications systems do not drop dramatically (which may be a flaw in their model because they usually do), then their analysis is on point and accordingly probably conservative from a PURELY financial analysis standpoint. Unfortunately, there is no way i can intelligently opine on the accuracy of their assumptions...But I .think it is a very good paper and should be shown to the major telecommunication companies. Perhaps they would want to explore this as a consortium.

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The Value Estimation of an HFGW Frequency Time Standard for Telecommunications Network Optimization

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Abstract. The emerging technology of gravitational wave control is used to augment a communication system using a development roadmap suggested in Stephenson (2003) for applications emphasized in Baker (2005). In the present paper consideration is given to the value of a High Frequency Gravitational Wave (HFGW) channel purely as providing a method of frequency and time reference distribution for use within conventional Radio Frequency (RF) telecommunications networks. Specifically, the native value of conventional telecommunications networks may be optimized by using an unperturbed frequency time standard (FTS) to (1) improve terminal navigation and Doppler estimation performance via improved time difference of arrival (TDOA) from a universal time reference, and (2) improve acquisition speed, coding efficiency, and dynamic bandwidth efficiency through the use of a universal frequency reference. A model utilizing a discounted cash flow technique provides an estimation of the additional value using HFGW FTS technology could bring to a mixed technology HFGW/RF network. By applying a simple net present value analysis with supporting reference valuations to such a network, it is demonstrated that an HFGW FTS could create a sizable improvement within an otherwise conventional RF telecommunications network. Our conservative model establishes a low-side value estimate of approximately $50B USD Net Present Value for an HFGW FTS service, with reasonable potential high-side values to significant multiples of this low-side value floor.

Keywords: high frequency gravitational waves, frequency time standard, communications, time difference of arrival, HFGW, FTS, TDOA, asset allocation

INTRODUCTION

According to Einstein (Einstein, 1918; Einstein, Rosen, 1937) and Weber (Weber, 1964), it has been derived for almost a century that gravitational waves exist as a mathematical solution, but as of the writing of this paper no definitive measurement of gravitational waves can be said to have taken place. Nevertheless it is worthwhile to explore the theoretically possible design space that is gravitational wave "technology." Because the strength of gravitational waves goes as the square of the 3rd derivative is seen in Eq.'s (1), (2), (Baker, Woods, and Li, 2006; Baker 2006), there is a particular interest in high frequency gravitational waves, by virtue of their relatively high power content.

From Einstein's General Theory of Relativity the power of a GW generator is given by his quadrupole equation. This equation can be written as shown in Eq. (1):

$$P(r, \Delta f, \Delta t) = 1.76\times10^{-52}\,(2r\Delta f/\Delta t)^2 \text{ W}, \tag{1}$$

where r is the radius of gyration of a mass in meters, Δf is an increment of force acting on a mass in Newtons during an incremental time period Δt in seconds. For a continuous series of acceleration changes, the frequency is ν_{GW} =

$1/\Delta t$, and Eq. [1] can be reformulated using HFGW frequency as:

$$P(r, \Delta f, v) = 1.76\times10^{-52}(2r\, v_{\mathrm{GW}}\, \Delta f)^2 \text{ W}. \tag{2}$$

Because the power increases with increasing frequency there is a special interest in high frequency gravitational waves, or HFGWs (100 kHz to greater than 100 THz). These HFGW emissions have previously been proposed as a means of communication (Stephenson, 2003.) This reference includes a survey of both transmitter and receiver designs.

HFGW AS A FREQUENCY TIME STANDARD

The scope of the present paper is to look the application of HFGW to the distribution of Frequency Time Standard data among what would otherwise be conventional telecom equipment. A typical worldwide distribution system could conceivably result in a number and configuration of the ground stations, shown in Fig. 1, where their latitude and longitude are given in parentheses.

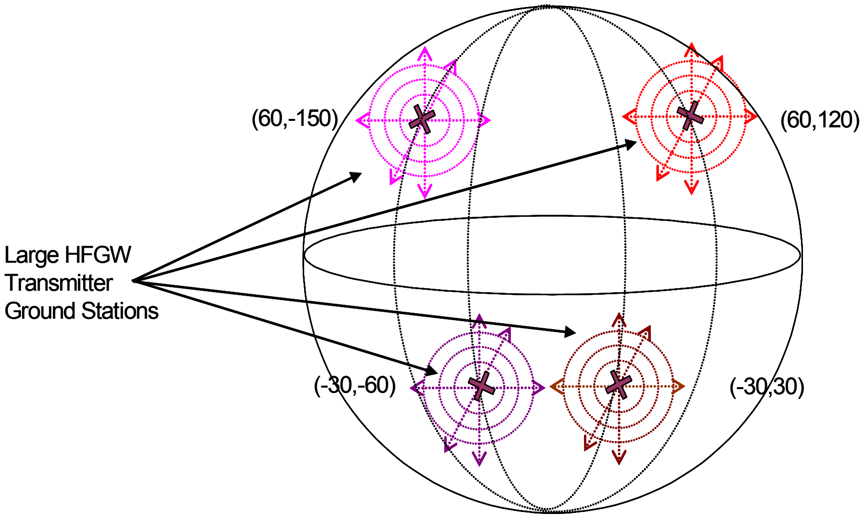


FIGURE 1. A Proposed Distribution of Frequency Time Standard.

The large transmitter ground stations would provide the signals used as both the frequency and time standards (FTS). All FTS ground stations would be synchronized such that they emit signals exactly in phase with each other, all tied to a common frequency time source, such as the US Naval Observatory. Each station would use a different frequency such that the remote terminal (RT) user set could easily differentiate signals, and any phase or time difference observed would be due to either the relative position of the remote terminal with respect to each ground station, or the relative velocity of the remote terminal with respect to each ground station. Each ground station would transmit both a carrier wave (CW) signal for a frequency reference and a periodic pulse signal (PPS) for a time reference. At least 3 ground stations would be needed for self-triangulation by the remote terminals, at least 4 with redundancy. HFGWs will propagate through the Earth with little modification, but very slight HFGW phase modification may be observed in surveillance applications (Baker, 2007.)

The counterpart to the fixed ground infrastructure would be the remote terminal side or user side of the FTS infrastructure. Each remote terminal would need to be equipped with a small HFGW receiver, which could pickup all 3 or 4 ground stations simultaneously. The arrival times of the received PPS signals could be compared via time difference of arrival, or TDOA, and used to develop a position estimate. The CW signal phases could be compared to determine the Doppler velocity of the remote terminal with respect to an Earth Centered Inertial (ECI) coordinate system. Thus, the HFGW FTS system could be used as a navigational aid, akin to the GPS system. This end of the infrastructure would be receive only and could therefore be a very low power device. Therefore mobile devices, such as cellular phones or web enabled personal digital assistants (PDAs) could be typical users of such a navigational service. An example is depicted in Fig. 2.

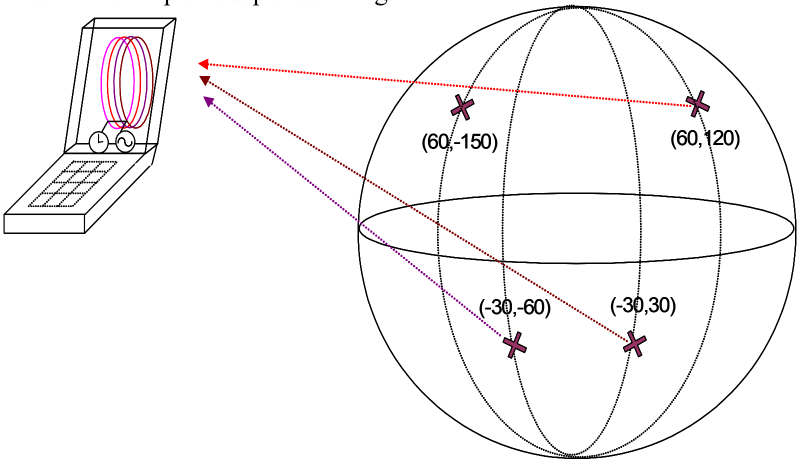


FIGURE 2. HFGW Supplemented Remote Terminal Design.

The navigational sensitivity of the HFGW receiver would depend on the frequencies used in the HFGW FTS system, as the received CW HFGW signal would act as the remote terminal's "built-in" frequency standard, replacing the need for internal crystal oscillators or Cesium or Rubidium standards. An HFGW FTS carrier wave with a frequency of 300 GHz with a wavelength of 1mm would result in 3 pico-second type time accuracy. The use of TDOA with these accuracies would allow for arbitrarily small navigational errors.

IMPROVEMENTS ACCRUING FROM A HFGW FREQUENCY TIME STANDARD

The cost of the FTS infrastructure must be more than balanced by the benefit resulting from that infrastructure if the cost is to be justified. Given that the GPS already provides adequate navigation services for most applications, navigational benefits alone would not justify the cost of an HFGW FTS system. However, in the case of a universal HFGW FTS, there are additional benefits associated with applying the frequency and time standards to standard telecommunications problems. The universal nature of the HFGW frequency and time standards are especially helpful. The following telecommunication benefits of an HFGW FTS system will be described in this section: improvement in acquisition time from search space improvements, improvements in modulation and coding efficiency from phase noise improvements, and improvements in bandwidth efficiency from frequency noise improvements.

Search Space Improvement Accruing from HFGW FTS

The following points are relevant with respect to the universal use of HFGW FTS among all remote terminals (including for instance cell phone handsets and their associated cellular towers):

- During signal acquisition the receiving terminal must perform a search of the search space of frequency, phase, and code to acquire the transmitting terminal signal.
- If there is less noise in these parameters the search space is reduced, speeding acquisition.
- Ultra-fast acquisition allows more efficient TDMA, or Time Domain Multiple Access style operations, such as transmit on demand, that use bandwidth more efficiently.

The smaller resultant search space is depicted graphically in Fig. 3.

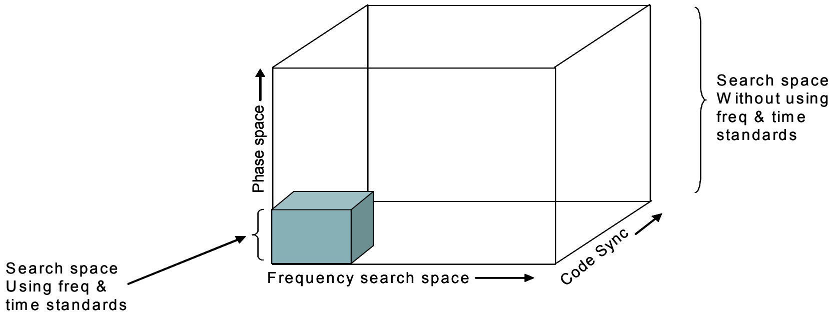


FIGURE 3. Acquisition Search Space Improvement Accruing from HFGW FTS.

An equation for acquisition search space time is presented in Eq. (3)

$$T_{acq} = N_{phase} * N_{freq} * N_{code} * (t_a) \tag{3}$$

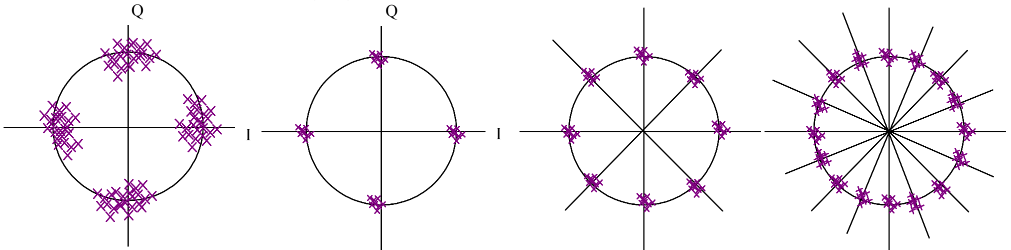
Where N_{phase} = number of phase space cases to check for acquisition
N_{freq} = number of frequency cases to check for acquisition
N_{code} = number of code sync possibilities to check
t_a = acquisition test time, per test case

In a typical example, if 30 MHz chipping is used with a 5 μsec error, there will be 150 code sync possibilities to check. If we also use a case where a frequency error of 1Hz within the acquisition window would cause a missed acquisition, and the worst case frequency error is 150Hz, then the number of frequencies that must be checked is also 150. Finally, we must check each possible phase possibility, say 16 different options for 16-PSK. PSK stands for Phase Shift Keying and is the encoding of data bits using incremental phase modulation. These acronyms are specified in the nomenclature section below. For a 5 μsec acquire test time, the result is Tacq =150*150*16*(5 μsec) = 1.8 seconds acquisition time.

However, with effectively perfect knowledge of time, frequency, and hence also phase, there will only be one case to check, so result is $T_{acq} = 1*1*1*(5\ \mu\text{sec}) = 5\ \mu\text{sec}$ acquisition time. This is essentially instantaneous for applications such as TCP/IP or VoIP. This will favorably impact the overall TDMA efficiency in that it speeds the claiming process to the point where an "always on" link can be replaced by a "link on demand." This is a savings of 25% to 50% in channel usage for VoIP and TCP/IP sessions over "always on".

The Impact of Phase Noise Improvements on Phase Shift Encoding

The use of a universal HFGW FTS would also benefit the relative phase noise of all terminals, allowing for finer phase encoding. Phase noise limits the type of modulation and manner of encoding that can be performed in phase space, commonly used for over the air telecommunication systems. An HFGW FTS system could reduce phase noise by providing a frequency reference with outstanding stability. For example, moving from QPSK to 8PSK or 16-PSK improves bandwidth efficiency by a factor of 2 to 4. The phase space improvement is summarized in Fig. 4.



(a) QPSK. **(b)** Low Noise QPSK. **(c)** Low Noise 8PSK. **(d)** Low Noise 16-PSK.

FIGURE 4. The Impact of Phase Noise Improvements on Phase Shift Encoding.

In the example of Fig. 4 nominal performance allows only QPSK, but improved phase noise would allow higher density phase encoding. Data rate will scale linearly with encoding efficiency as shown in Eq. (4):

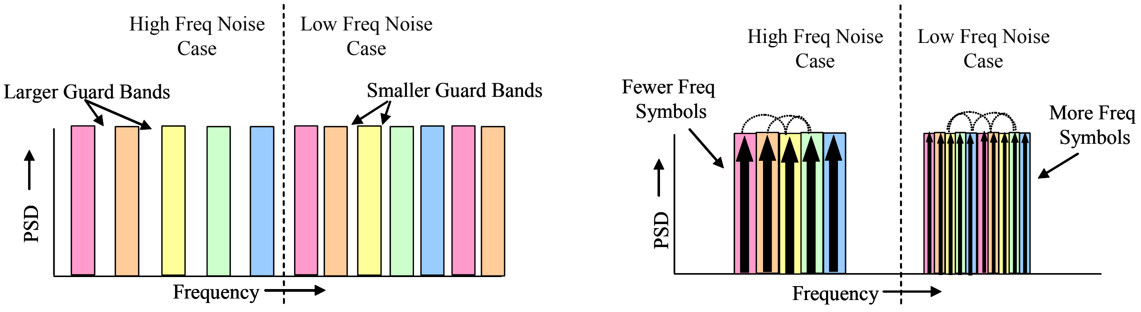
$$\text{Data Rate} = (BW/2)*(\text{Coding Efficiency})*(\text{FEC Rate}) / (\text{PN Spreading Factor}) \tag{4}$$

Coding efficiency will be a factor of 2 better when moving from QPSK to 8PSK, or a factor of 4 better when moving from QPSK to 16-PSK. This will translate directly into a linear increase in the allowable data rate that a given bandwidth can support. Put another way, a universal frequency time standard could quadruple over the air bandwidth efficiencies just by improving phase noise alone. Phase noise improvements would be limited only by the slight variations induced in the HFGW signal passing through the earth as described in Baker (2007).

The Impact of Frequency Noise Improvements on FDMA and FHSS

The very low noise frequency standard that would be supplied by an HFGW FTS system would allow for much more efficient use of reserved frequency bandwidth. Frequency noise limits the type of modulation and manner of encoding that can be performed in frequency space, such as Frequency Division Multiple Access (FDMA) or Frequency Hopping Spread Spectrum (FHSS). HFGW can reduce frequency noise by providing a frequency reference with outstanding stability. For example, guard bands can be shrunk in FDMA, and frequency slices can be smaller and more stable in FHSS.

A frequency space representation of the FDMA and FHSS noise improvements are depicted in Fig. 5:



(**a**) Frequency Division Multiple Access.

(**b**) Frequency Hop Spread Spectrum.

FIGURE 5. The Impact of Frequency Noise Improvements on FDMA and FHSS.

Efficiencies in guard band structure can be defined as in Eq. (5).

$$\text{Guard band BW Efficiency} = (\text{Total Bandwidth-}\{\text{Sum of Guard BW}\})/\text{Total Bandwidth} \tag{5}$$

Guard bands often consume 30% to 50% of assigned frequency space. While guard bands would still be required to allow for the sidelobes of signals, the frequency error component would be eliminated. Similar efficiencies may be gained in the FHSS approach. A better knowledge of absolute frequency allows better frequency coding efficiencies, as seen in Eq. (4) and depicted in Fig. 5.

COST OF HFGW INFRASTRUCTURE VERSUS SAVINGS IN TELECOM OPS

Our approach is to use low-side technical and financial assumptions to establish a basement for our simple conservative valuation estimate. Further, while we feel strongly about the upside due to new market using an affordable HFGW FTS, we have also chosen to leave new market benefits out of the estimate to be addressed separately. Similarly, we treat as an external variable the optimizations from demand-side prioritized rate control enabled by HFGW FTS. The precision delay and congestion measurement enable efficient distributed pricing and globally optimized distributed resource allocation (MacKie-Mason and Varian, 1995). We have included high-side estimates as merely a reference. We do not view these as a ceiling as the unprecedented capability of this FTS stands to enable further, perhaps also unprecedented engineering exploitation during the life of even the initial HFGW FTS service.

- For search space improvements we choose 25%. For higher density phase encoding due to phase noise improvement, we choose 200%. For frequency-based improvements, we choose 25% for an overall raw capacity improvement floor of 250%.

- For better beam-forming due to precision positioning, we choose not to include this technology in the low side estimate since it is somewhat speculative. For the high side estimate 50% is used.
- For cell-handoff and precision Quality of Service (QoS) improvements due to precision timing, we choose an overall value improvement of 200%. Here, we apply the term QoS to network usage prioritization and predictability with respect to performance parameters including delay, error rate, and throughput.
- Even as a floor, we significantly reduce these expected low-side improvements prior to further use in our dollar valuation model to reinforce its conservative nature.

TABLE 1. HFGW Technical Improvement Value Estimate.

Low-Side Technical Improvement		*(High-Side Reference)*
Search Space	25%	*50%*
High Density Phase Enc.	200%	*400%*
Frequency Noise (TBE)	25%	*50%*
Positioning/Beam Forming	0%	*50%*
Raw Capacity Improvement	*250%*	*550%*
+ Precision QoS Enablement	*200%*	*1000%*
Model's Simplifying Multiplier:	*450%*	*1550%*

Applying these multipliers to a conventional High Bit Rate Wireless Market Offer (conservatively—for this model—priced at $100/month/2Mbps), we obtain a reference MRC/subscriber low-side value added due to the HFGW FTS of $275 (Table 2). Note that MRC = Monthly Recurring Charge. This includes a 25% $/mbps discount from conventional costs due to supply increase and demand elasticity. Further, in all significant cash flows (post year 2), we utilize a still more conservative estimate ranging from ~75-15% of this reference value.

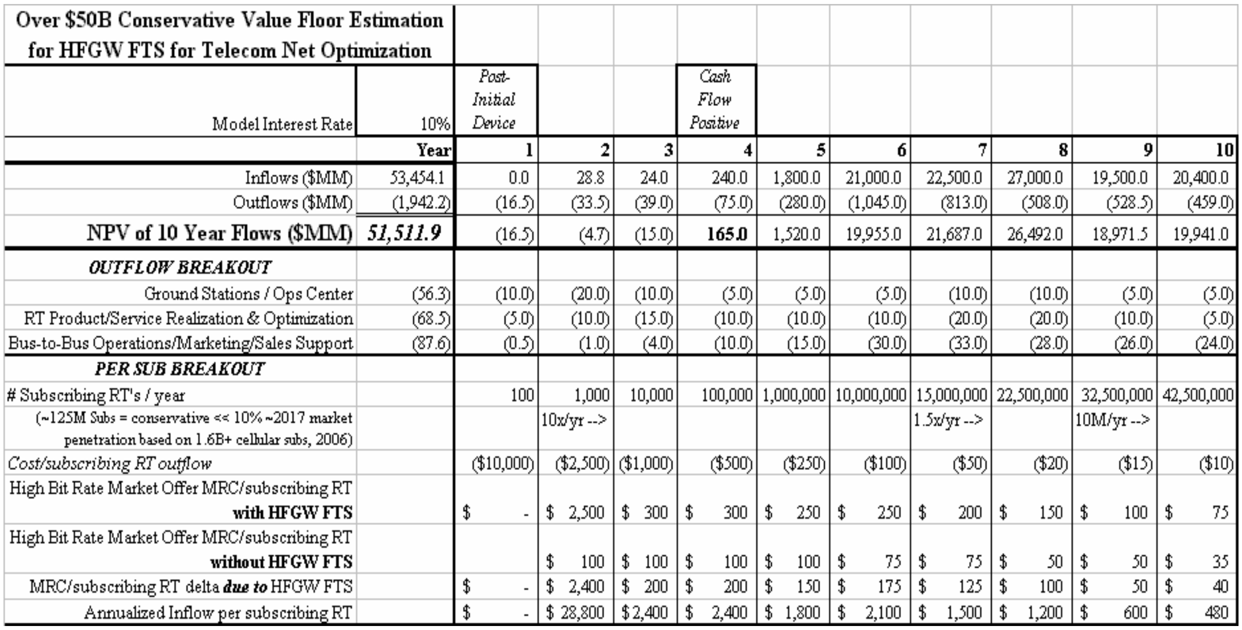
TABLE 2. HFGW MRC Subscriber Added Value Estimate.

Reference MRC / Subscriber Value Add	Mbps	$/month	$/Mbps/mo
High Bit Rate Wireless Market Offer	2	$ 100	$ 50
Simplifying 2.5x bit rate multiplier from raw capacity improvement	5	$ 188	$ 37.50 *
Simplifying 2x $value multiplier from precision timing/QoS enablement	5	$ 375	$ 75
Reference: MRC/subscriber low-side value add due to HFGW FTS		$ 275	

** 25% $/mbps discount from conventional*

We built a simple value estimation model for a HFGW FTS service utilizing a discounted cash flow technique which simply adds up our estimated cash inflows and outflows over the first ten years of such a service (post the first working device) and accounts for the time value of money at 10% (model). (See Table 3). Based on the reduced inputs above, conservative market penetration, and model assumptions for end-to-end product and service realization and operations, as well as simplifying demand/supply and technology refresh interactions over the service life, we have arrived at a rough estimate of the HFGW FTS value floor. We estimate approximately $50B Net Present Value for HFGW FTS service for optimization of otherwise conventional telecommunications networks. While we have a significant cost drop factored in already, to get a better sense of worst case risk due to unforeseen circumstances, we further considered such scenarios as a drastic (~90%) drop in costs for conventional telecommunications network capacity and an ~1000% increase in ground station buildout and product development costs. Since neither of these situations is truly unheard of, we wanted to see if an HFGW FTS would still be a good investment. We found that even in the face of both these drastic events, our already conservative model still manages to yield a positive Net Present Value. This is favorable from a risk perspective, suggesting that even in this worst case this service should still make money in real dollar terms.

TABLE 3. HFGW FTS Value Estimation by Year, Post-Initial Device.



Over $50B Conservative Value Floor Estimation for HFGW FTS for Telecom Net Optimization											
Model Interest Rate	10%	*Post-Initial Device*			*Cash Flow Positive*						
	Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Inflows ($MM)	53,454.1	0.0	28.8	24.0	240.0	1,800.0	21,000.0	22,500.0	27,000.0	19,500.0	20,400.0
Outflows ($MM)	(1,942.2)	(16.5)	(33.5)	(39.0)	(75.0)	(280.0)	(1,045.0)	(813.0)	(508.0)	(528.5)	(459.0)
NPV of 10 Year Flows ($MM)	***51,511.9***	(16.5)	(4.7)	(15.0)	**165.0**	1,520.0	19,955.0	21,687.0	26,492.0	18,971.5	19,941.0
OUTFLOW BREAKOUT											
Ground Stations / Ops Center	(56.3)	(10.0)	(20.0)	(10.0)	(5.0)	(5.0)	(5.0)	(10.0)	(10.0)	(5.0)	(5.0)
RT Product/Service Realization & Optimization	(68.5)	(5.0)	(10.0)	(15.0)	(10.0)	(10.0)	(10.0)	(20.0)	(20.0)	(10.0)	(5.0)
Bus-to-Bus Operations/Marketing/Sales Support	(87.6)	(0.5)	(1.0)	(4.0)	(10.0)	(15.0)	(30.0)	(33.0)	(28.0)	(26.0)	(24.0)
PER SUB BREAKOUT											
# Subscribing RT's / year		100	1,000	10,000	100,000	1,000,000	10,000,000	15,000,000	22,500,000	32,500,000	42,500,000
(~125M Subs = conservative << 10% ~2017 market penetration based on 1.6B+ cellular subs, 2006)			10x/yr -->					1.5x/yr -->		10M/yr -->	
Cost/subscribing RT outflow		($10,000)	($2,500)	($1,000)	($500)	($250)	($100)	($50)	($20)	($15)	($10)
High Bit Rate Market Offer MRC/subscribing RT **with HFGW FTS**		$ -	$ 2,500	$ 300	$ 300	$ 250	$ 250	$ 200	$ 150	$ 100	$ 75
High Bit Rate Market Offer MRC/subscribing RT **without HFGW FTS**			$ 100	$ 100	$ 100	$ 100	$ 75	$ 75	$ 50	$ 50	$ 35
MRC/subscribing RT delta ***due to*** HFGW FTS		$ -	$ 2,400	$ 200	$ 200	$ 150	$ 175	$ 125	$ 100	$ 50	$ 40
Annualized Inflow per subscribing RT		$ -	$ 28,800	$ 2,400	$ 2,400	$ 1,800	$ 2,100	$ 1,500	$ 1,200	$ 600	$ 480

CONCLUSION

A conceptual design for an HFGW Frequency Time Standard system was presented that is predicted to result in a number of potentially valuable enhancements to existing telecommunication systems. Enhancements could include improved TDMA due to better time knowledge, improved phase shift encoding efficiency due to lower phase noise, and improved FDMA and FHSS efficiencies due to better frequency knowledge. The worldwide deployment of an HFGW FTS system was conservatively estimated to accrue $50 Billion in value over the first 10 years of operation. Note this does not include the R&D costs associated with development of the initial HFGW technology itself.

$50B is a large sum by any measure. When stepping back, does this figure stand the test of reason? Switching from a bitrate to a bandwidth-oriented view may further amplify the system. Based on government auctions and secondary markets, wireless bandwidth license valuations range anywhere from ~$0.10/Mhz/pop to $3.00/Mhz/pop, depending on, among other things, frequency and geographic location. A “pop” (point of presence) in this context refers to a potential service user residing in an area where a licensee has signal coverage and can provide service including areas where they may not have yet commenced service. As a potential HFGW FTS-enabled Remote Terminal subscriber, a pop is another fair reference against which to check the reasonableness of our value estimation. Even assuming as few as 2B pops, only $0.05/Mhz/pop, and with the HFGW FTS capacity multiplier applied to only 1000 MHz globally, potentially $150B could be created in additional value.

More specifically, one of the U.S. FCC’s last decade’s auctions (Auction 14 for Wireless Communications Services in ’97) brought ~$14B for 30Mhz approximately nationwide coverage. Applying the 2.5x simple capacity multiplier, another potentially $20B (low-side) in value could be created in these bands alone.

As noted earlier, we have chosen not to factor new market enablement or market-oriented demand-side optimizations into our estimates. These include though are not limited to RT’s with dual participation in sensor nets due to search space improvement, extending precision FTS service to higher-level applications and to locations currently unreachable by conventional precision GPS-based systems.

For all these reasons, we view our value estimation—even at an order of magnitude smaller--as sufficiently conservative, supportable, and transparent to merit serious ongoing dialog regarding commercialization of an HFGW FTS service.

NOMENCLATURE

BW = Bandwidth (Hz)
CW = Carrier Wave
Δf = Incremental Force (Newtons)
Δt = Incremental Period (seconds)
GW = Gravitational Wave
8PSK = Eight Phase Shift Keying
FCC =
Federal Communications Commission
FEC = Forward Error Correction code
FHSS = Frequency Hopping Spread Spectrum
FDMA = Frequency Division Multiple Access
FTS = Frequency Time Standard
GPS = Global Positioning System
HFGW = High-Frequency Gravitational Wave
MRC = Monthly Recurring Charge
N_{code} = number of code sync possibilities
N_{freq} = number of frequency cases
N_{phase} = number of phase space cases
NPV = Net Present Value
P = Power (Watts)
PN = Pseudo Noise
PPS = Periodic Pulsed Signal
PSK = Phase Shift Keying
QoS = Quality of Service
QPSK = Quadrature Phase Shift Keying
r = radius of gyration (meters)
RT = Remote Terminals
16-PSK = Sixteen Phase Shift Keying
t_a = Acquisition Time (seconds)
TDMA = Time Domain Multiple Access
TDOA = Time Difference of Arrival
ν = Frequency of Periodic Force (Hz)
ν_{GW} = Frequency of Quadrupolar GW (Hz)

ACKNOWLEDGMENTS

For their encouragement as well as helpful and substantial comments, we wish to thank Dr. Robert M. L. Baker, Jr. and Paul Murad.

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