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Shallow water limits to hydro-acoustic communication baud rate and bit energy efficiency

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ABSTRACT

Shallow water hydro-acoustic communication channels are characterised by transient multipath signals which limits maximum baud rate and peak bit energy efficiency. Precision measurements of multiple shallow and deep water environments, using multi-channel direct sequence spread spectrum modems, establish a relationship between maximum baud rate and peak bit energy efficiency as a function of transmit power, communication range, water depth, and ambient noise. Bit energy efficiency peaks at a lower baud rate than the shallow water inter-symbol interference bounded maximum baud rate. Operating multi-channel direct sequence spread spectrum modems at peak bit energy efficiency provides maximum covert performance and minimum battery power consumption with the potential of establishing long range network routed communication links powered by ocean energy harvesting.

1 INTRODUCTION

Multi-Channel Direct Sequence Spread Spectrum (MCDSSS) hydro-acoustic modems are used to provide a guarantee of service for mission critical long-range underwater communication as used on the 2012 Mariana Trench $11\ \mathrm{km}$ depth submarine dive [Roberts et al 2012]. MCDSSS signaling also provides covert communication up to a Transmit Margin of $M_{TX} \approx 12\ \mathrm{dB}$ below the ocean noise floor. MCDSSS message reliability for non-covert communication is approximately 100% however shallow water performance in Australia, Baltic and Singapore measured message reliability at approximately 80% for covert communication. Subsequent failure analysis identified the multipath arrival delay structure as the limit to message reliability, which induces a different MCDSSS receiver failure mode for different channel geometries. Incremental MCDSSS message reliability improvements, approaching 99%, were quantified via multiple sea trials which measured the minimum transmit power as a function of hydro-acoustic baud rate. As message reliability improved the variance in the performance measurements decreased to reveal a non-linear relationship between the hydro-acoustic baud rate (Br) and bit energy efficiency (BEE). BEE peaks at a lower baud rate than shallow water inter-symbol interference bounded maximum baud rate with a transmit Sound Pressure Level (SPL_{BEE}) low enough to establish a long-range network routed communication link powered by ocean energy harvesting.

2 HYDRO-ACOUSTIC TEST

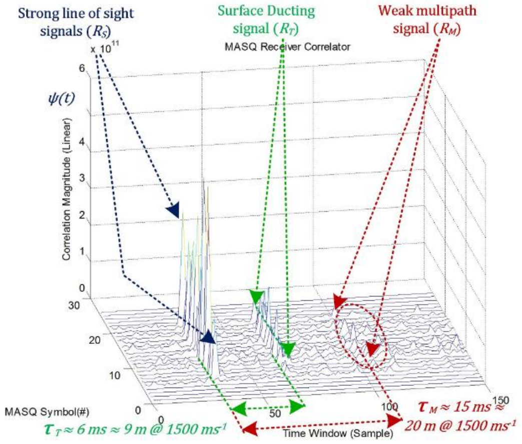
The hydro-acoustic test sites were $100\ \mathrm{km}$ and $50\ \mathrm{km}$ west of Fremantle Western Australia (WA), Cockburn Sound, Fremantle Harbour and L3 Oceania hydro-acoustic tank (Figure 1).

Source (Author, 2017)
Figure 1: Australian west coast test sites

The ambient noise, across the $6.5\ \mathrm{kHz}$ to $16.5\ \mathrm{kHz}$ communication band, varied from $45\ \mathrm{dB\ re\ 1\mu Pa/\sqrt{Hz}} \cong$ Sea State 1 ($SS1$) calm seas, to $75\ \mathrm{dB\ re\ 1\mu Pa/\sqrt{Hz}} \cong SS6$ very loud in-shore snapping shrimp, equivalent to heavy rain. Tests were carried out in water depths from $3\ \mathrm{m}$ to $2\ \mathrm{km}$. The equipment under test was the L3 Oceania GPM300 MCDSSS hydro-acoustic network modems, which support hydro-acoustic baud rates from 10 to $1{,}000$ baud and transmit Sound Pressure Levels (SPL) from $190\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1m}$ ($\cong 100\ \mathrm{W_A}$) to $130\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1m}$ ($\cong 100\ \mathrm{\mu W_A}$) in $1\ \mathrm{dB}$ steps. The modems were calibrated in the L3 Oceania Hydro-acoustic tank for transmit power (PSD_{TX}) to $\pm 1\ \mathrm{dB}$, receive power (PSD_{RX}) measurements to $\pm 2\ \mathrm{dB}$ and absolute ambient noise (PSD_A) measurements to $\pm 2\ \mathrm{dB}$. Remote modem PSD_{RX} and PSD_A measurements were retrieved via hydro-acoustic network routing. Slant range (R_s) was measured using transpond or one-way time of flight.

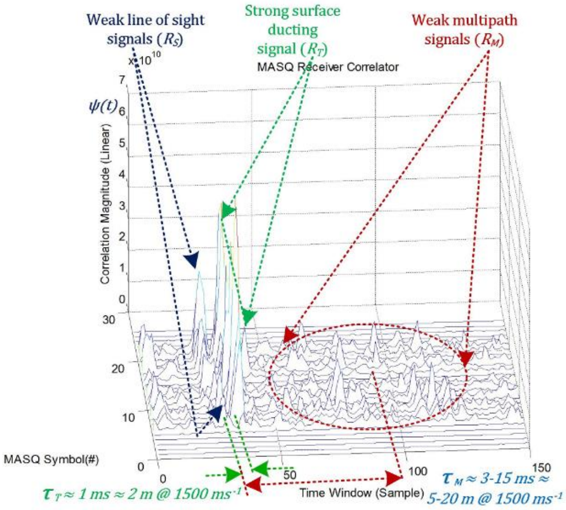
3 CHANNEL MULTIPTH CHARACTERISTIC

Figure 2 illustrates the measured $3.4\ \mathrm{km}$ range multipath structure $50\ \mathrm{km}$ west of Fremantle in $130\ \mathrm{m}$ water depth for a 1 m depth transmitter and 30 m depth receiver which is characterised by strong line of sight signal (R_S) followed by $9\ \mathrm{m}$ surface ducting signal (R_T) and $20\ \mathrm{m}$ multipath reflections (R_M).



Source (Author, 2017)
Figure 2: Australian west coast multipath 3.4 km range 130 m water depth

Figure 3 illustrates the measured $9.7\ \mathrm{km}$ range multipath structure $50\ \mathrm{km}$ west of Fremantle in $130\ \mathrm{m}$ water depth for a $1\ \mathrm{m}$ depth transmitter and $30\ \mathrm{m}$ depth receiver which is characterised by weak line of sight signal (R_S) followed by a $2\ \mathrm{m}$ strong surface ducting signal (R_T) and $5\ \mathrm{m}$ to $20\ \mathrm{m}$ weak multipath reflections (R_M)



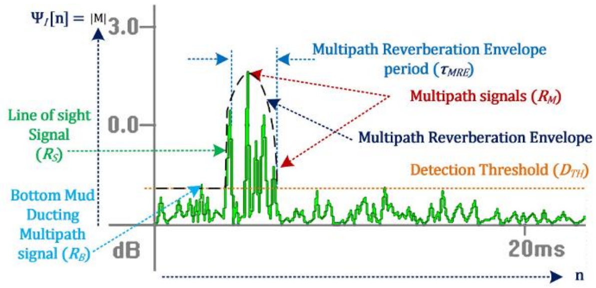
Source (Author, 2017)
Figure 3: Australian west coast multipath 9.7 km range 130 m water depth

4 MAXIMUM HYDRO-ACOUSTIC BAUD RATE

The maximum hydro-acoustic baud rate (Br_{MAX}) is limited by the multipath reverberation envelope period (τ_{MRE})

(Figure 4). A MCDSSS recevier cannot detect multipath reverberation signals (R_M) when the multipath correlation magnitude (Ψ_M) drops below the ambient noise floor (PSD_A) by more than the transmit margin (M_{TX}) ($\text{i.e. } \Psi_M < PSD_A - M_{TX}$). The multipath reverberation envelope period (τ_{MPE}), excluding the bottom ducting mud signal (R_B), is the time difference between the line of sight signal (R_S) and the last multipath signal above the detection threshold (D_{TH}), and is proportional to channel aspect ratio which is a function of the communication range (R_S) and ocean ducting depth (R_{DD}) Eq.(1).

$$\tau_{MPE} \cong \mathrm{MAX}(t_{RX}[n] - t_{RX}[0]) \text{ for } \Psi_I[n] > D_{TH}, \quad \tau_{MPE} \propto \frac{R_S}{R_{DD}} \tag{1}$$

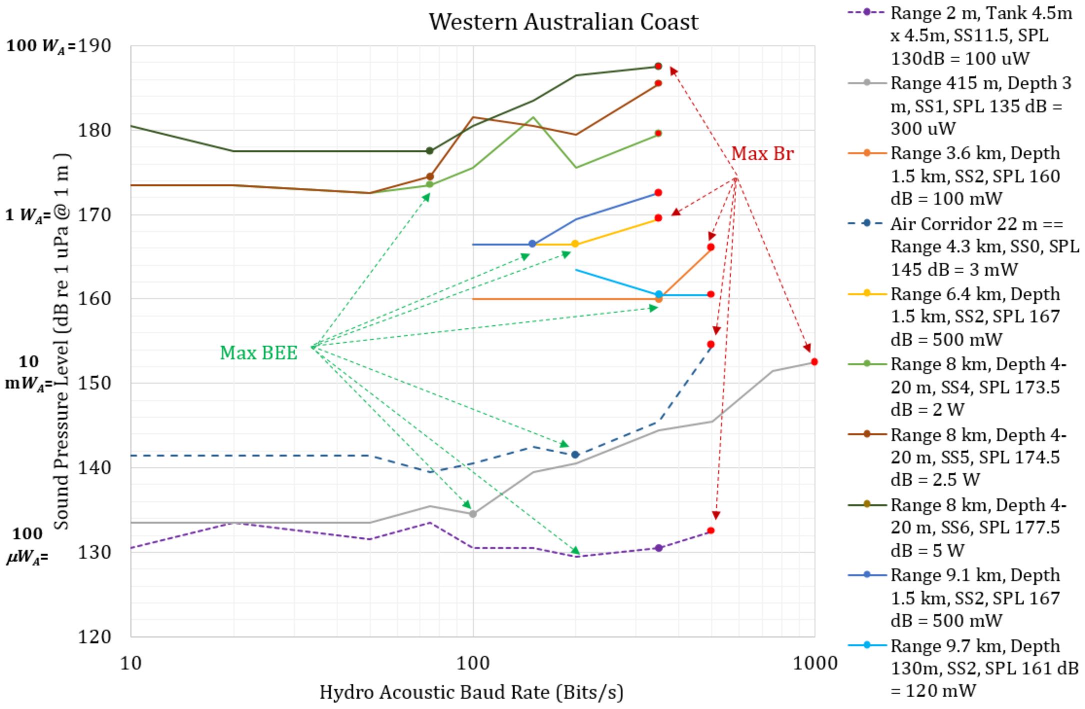


Source (Author, 2017)
Figure 4: MCDSSS receiver multipath reverberation envelop

The off shore hydro-acoustic test baud rate symbol period was varied from 10 baud ($\tau_{SY} \approx 800\text{ ms}$) to $1{,}000\text{ baud}$ ($\tau_{SY} \approx 32\text{ ms}$). The sea trial τ_{MRE} varied from 2 ms to 50 ms and when it exceeds the hydro-acoustic baud rate symbol period (τ_{SY}) will limit the maximum hydro-acoustic baud rate (Br_{MAX}).

5 MINIMUM TRANSMIT POWER

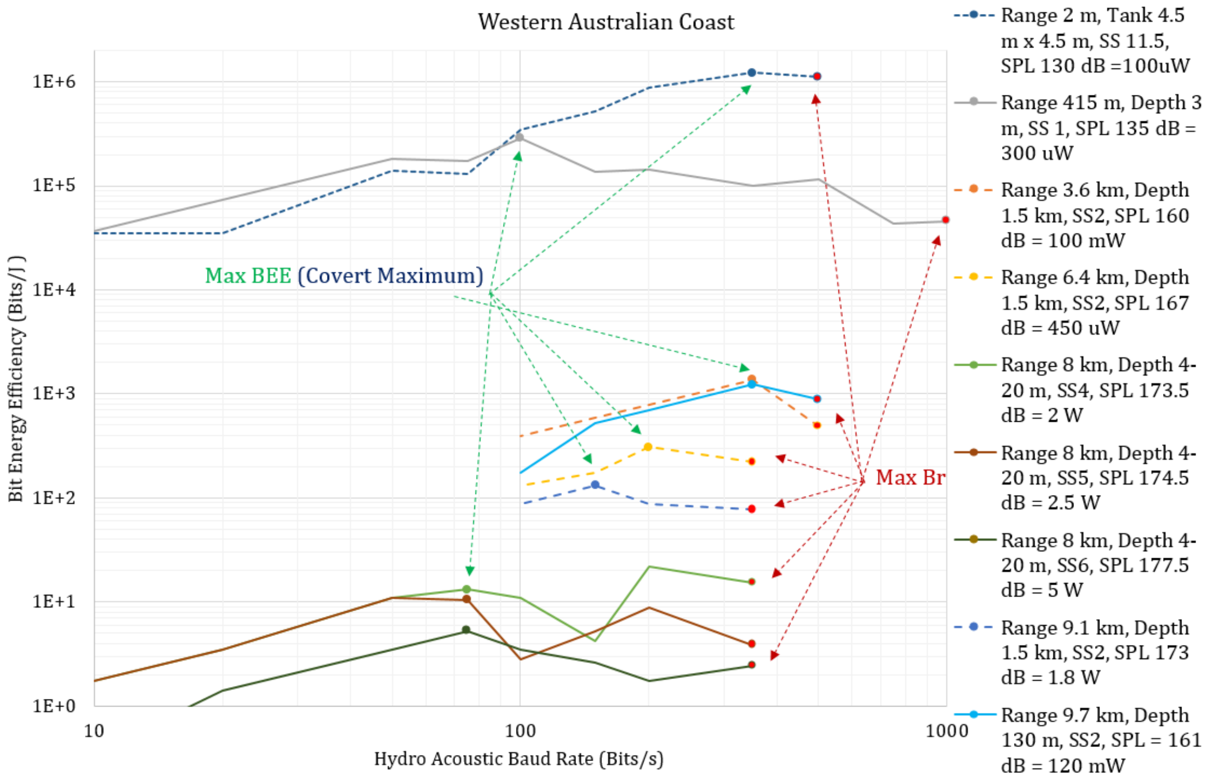
Figure 5 illustrates the measured minimum transmit power (SPL_{MIN}) verses hydro-acoustic baud rate as a function of slant range (R_S), water depth (R_D) and sea state (SS). The maximum hydro-acoustic baud rate (Br_{MAX}), 50 km off the Australian west coast, was limited to 500 baud for communication ranges greater than 10 km in 130 m water depth, SS2. The Cockburn Sound 8 km range, SS6 and 4 m to 20 m depth environment maximum baud rate (Br_{MAX}) was limited to 350 baud.



Source (Author, 2017)
Figure 5: MCDSSS minimum transmit power verses hydro-acoustic baud

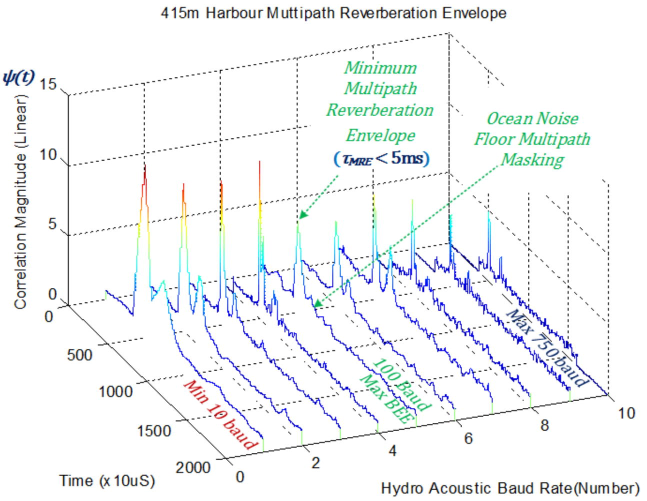
6 PEAK BIT ENERGY EFFICIENCY (BEE)

Figure 6 illustrates the measured BEE verses baud rate as a function of slant range (R_S), water depth (R_D) and sea state (SS).



Source (Author, 2017)
Figure 6: Bit energy efficiency verses baud rate

Figure 7 illustrates the multipath envelope verses baud rate from 10 baud to 750 baud as measured in a 415 m range and 3 m to 5 m depth channel. The maximum attempted baud rate was 1,000 baud, but BEE peaked at 100 baud where the multipath envelope, other than the strongest arrival, is masked by the ocean ambient noise. Faster baud rates require higher transmit power to maintain the energy per bit however louder transmit signals also increase the self-noise multipath reverberation envelope period (τ_{MRE}).



Source (Author, 2017)
Figure 7: Multipath envelope verses baud rate

Transmit power (SPL_{TX}) can be related to electrical power ($\mathrm{P_E}$) using the electrical to acoustic power efficiency (ϵ_{TX}) which is typically 35% to 40% for a 100 $\mathrm{W_A}$ MCDSSS modem as per Eq.(2).

$$\mathrm{P_E} \approx \frac{100}{\epsilon_{TX}} 10^{\left(\frac{SPL_{TX} - SPL_{1W_A}}{10}\right)} \text{ for } \mathrm{P_E} > \mathrm{P}_{Q_{TX}}$$

$$SPL_{1W_A} \approx 170.5 \text{ dB re } 1\mu\text{Pa @ 1 m /1 W}_\text{A} \tag{2}$$

$$\mathrm{P}_{Q_{TX}} \approx 3 \text{ W}_\text{E} \text{ quiescent power for 100 W}_\text{A} \text{ MCDSSS modem}$$

Equation 3 described the difference in transmit power (ΔSPL_{TX}) required for a communication range (R_S) relative to $R_{REF} = 1{,}000$ m.

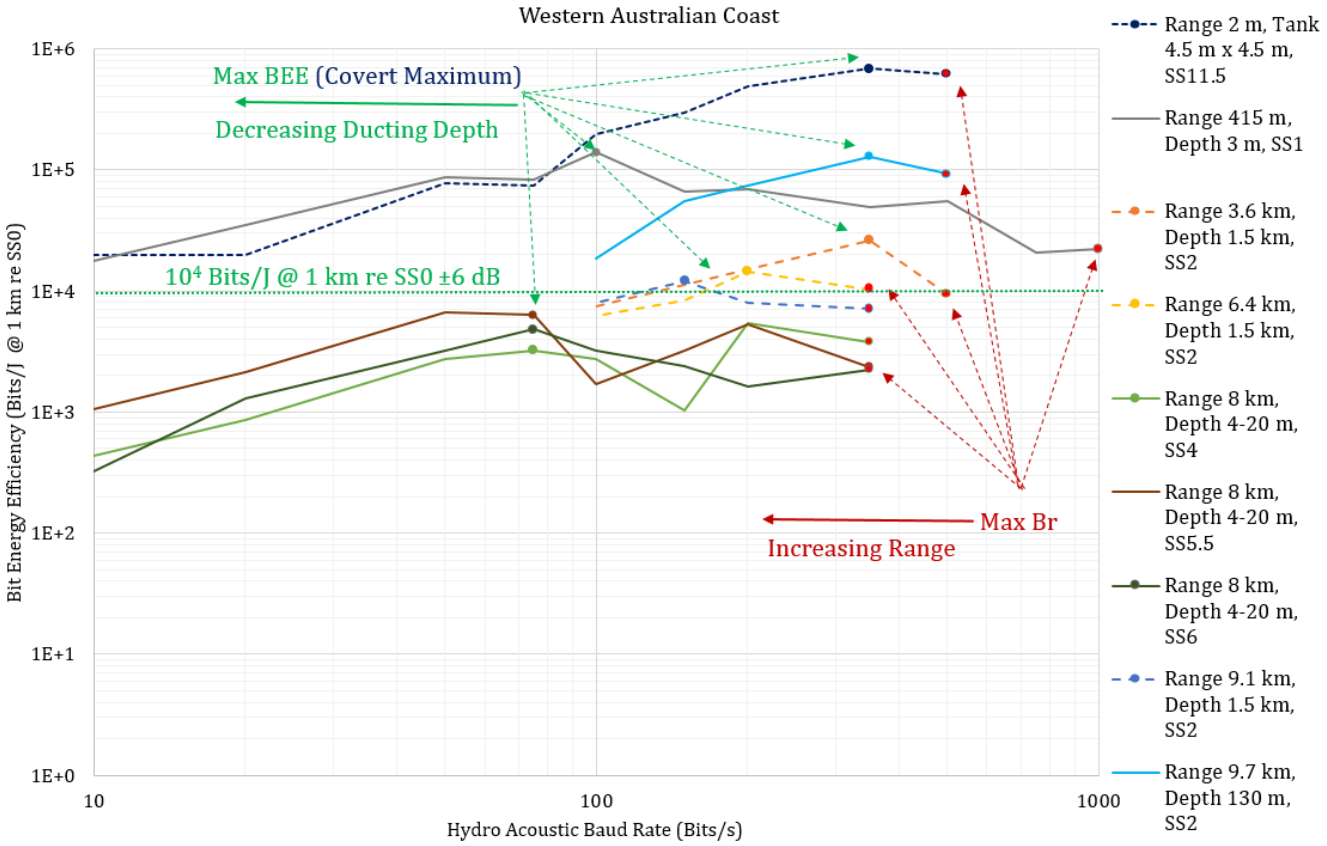
$$\Delta SPL_{TX} \approx \left(20log_{10}(R_S) + \frac{R_S}{1{,}000} G_A\right) - \left(20log_{10}(R_{REF}) + \frac{R_{REF}}{1{,}000} G_A\right)$$

$$R_{REF} = 1{,}000 \text{ m}, \; G_A \approx 1 \; dB/km \text{ (for MCDSSS 6.5 kHz to 16.5 kHz)} \tag{3}$$

When BEE is normalised for communication range and sea state (Figure 8) the MCDSSS nominal peak BEE_{PEAK} is approximately 10^4 Bits/J @ 1 km re SS0 $\pm$ 6 dB and can be used to predict the maximum operating sea state ($SS\#$) as a function of communication range (R_S) for a hydro-acoustic baud rate (Br_{BEE}) Eq.(4).

$$SS\# \approx \left(10log_{10}\left(\frac{BEE_{PEAK} \times Br_{BEE}}{\mathrm{P_E}}\right) - \Delta SPL_{TX}\right) / SS_{PSD}, \pm 1 \; SS$$

$$SS_{PSD} \approx 6 \; dB/SS \tag{4}$$



Source (Author, 2017)

Figure 8: MCDSSS measured bit energy efficiency normalized to 1 km re SS0

The baud rate for BEE_{PEAK} as a function of communication range, was found to be limited between 50 baud to 500 baud depending on sea state, water depth or surface ducting depth as summarised in Table 1.

Table 1: Western Australia coast peak BEE measurement summary

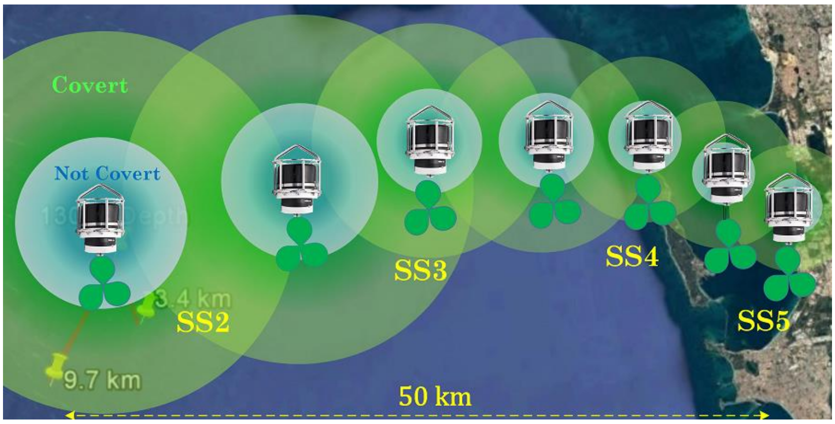
Location	**Range** (m)	**Depth** (m)	**Ducting$_{\text{Depth}}$** (m)	**Aspect Ratio**	**Sea State**	**SPL$_{\text{Min}}$** (dB re 1 μPa @ 1m)	**Br$_{\text{Max}}$** (baud)	**BEE$_{\text{Peak}}$** (baud)
L3 Oceania tank	2	4.5	0 to 4.5	1:2	0 to +12	130	500	350
Fremantle Harbour	400	3 to 5	0 to 5	1:300	1 to 4	135	1000	100
Cockburn Sound	8,000	4 to 20	0 to 20	1:500	5 to 6	174	350	75
50 km west of WA	10,000	130	0 to 20	1:500	2 to 4	161	500	350
100 km west of WA	10,000	1,500 to 2,500	0 to 100	1:100	2 to 4	167	350	150

7 SUMMARY

In the logarithmic physical world energy radiates spherically but in engineering environments energy is propagated via cables and transducers where linear power savings gains are modest. MCDSSS peak bit energy efficiency BEE_{PEAK} has significant implications for the powering of long range hydro-acoustic communication links, because logarithmic power savings can be realised by measuring the maximum BEE_{PEAK} as a function of baud rate (Br_{BEE}) and minimum transmit power (SPL_{MIN}).

The MCDSSS communication range and sea state normalised $BEE_{PEAK} \approx 10^4\ \mathrm{Bits/J\ @\ 1\ km\ re}\ SS0$ roughly translates to $1\ \mathrm{km}$ hydro-acoustic communication requiring $SPL_{TX} \approx 166\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1\ m} \cong 0.35\ \mathrm{W_A} \cong 1\ \mathrm{W_E}$ of power for $10{,}000\ \mathrm{baud}$ link however shallow water multipath envelope period ($\tau_{MPE} < 50\ \mathrm{ms}$), with ducting depths less than $100\ \mathrm{m}$, will limit the maximum baud rated to less than $1{,}000\ \mathrm{baud}$ ($\tau_{SY} > 32\ \mathrm{ms}$). The $9.7\ \mathrm{km}$ range, $130\ \mathrm{m}$ depth, SS2, $Br_{BEE} = 350\ \mathrm{baud}$ communication link required a minimum transmit power of $160\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1m} \cong 0.1\ \mathrm{W_A}$ which requires $0.3\ \mathrm{W_E}$ of electrical power assuming a total MCDSSS transmitter electrical efficiency of approximately 35%. The L3 GPM300 Modem will deliver a maximum SPL of $190\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1\ m} \cong 100\ \mathrm{W_A}$ requiring $300\ \mathrm{W_E}$ electrical power however the transmitter power amplifier and signal processing hardware quiescent power is approximately $\mathrm{P}_{\mathrm{Q}_{TX}} \approx 3\ \mathrm{W_E}$ and does not minimise battery consumption when transmitting at SPL's less than $175\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1m} \cong 3\ \mathrm{W_A}$. Equation 4 estimates that three $100\ \mathrm{W_A}$ MCDSSS network routing modems can establish a short-term battery powered $50\ \mathrm{km}$ range communication link, in SS2 to SS5 shallow water using $SPL_{TX} = 185\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1\ m}$ ($\cong\ 30\ \mathrm{W_A}$) transmit power.

Equation 4 predicts that seven electrically efficient $1\ \mathrm{W_A}$ MCDSSS network routing modems could establish a semi-permanent $50\ \mathrm{km}$ range communication link, in SS2 to SS5 shallow water using $SPL_{TX} = 165\ \mathrm{dB\ re\ 1\ \mu Pa\ @\ 1\ m}$ ($\cong 0.3\ \mathrm{W_A}$) transmit power in conjunction with ultra low power signal processing assuming $1\ \mathrm{W_E h}$, for continuous transmission, can be harvested from the ocean (Figure 9). The $0.5\ \mathrm{kn}$ ocean bottom current, ocean waves or a thermocline could be used to harvest energy to charge a battery as long as the energy harvesting mechanism hydro-acoustic noise is less than the ocean noise floor.



Source (Author, 2017)

Figure 9: 50 km ocean powered communication link (1 $\mathrm{W_A}$ modem)

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