OPTIMIZING APPLICATIONS AND DATA LINKS FOR HF RADIO INTERMEDIATE TERM VARIATION: CAN YOU RIDE THE WAVE?

Steve Kille
Isode Ltd
Hampton, UK
steve.kille@isode.com

SUMMARY

HF Radio transmission is subject to a wide range of variations. Much analysis has been devoted to Rayleigh Fading and other variations in signal over periods of a few seconds. Modem and waveform design has been focussed to address these short term variations. There are also longer term variations, which were initially modelled in "The Walnut Street Model of Ionospheric HF Radio Propagation" [1]. This modelling was refined by a group at Harris Corporation which broke down the variation into two basic elements: Intermediate Term Variation (ITV) and Long Term Variation [2]. Isode in collaboration with Rockwell Collins made measurements of ITV in 2014 which fitted well with the ITV model and were reported on at HF Industries Association in September 2014 [3] and in a subsequent white paper [4].

The work cited shows that ITV has a significant effect on the error patterns seen above the modem level. Errors at the modem level which are not detected and passed upwards will need to be addressed at link level or application level. Choice of HF parameters and in particular transmission speed is key to optimizing throughput or latency. The STANAG 5066 link layer is widely used with HF and performance has usually been optimized for throughput. Transmissions are made for periods of up to two minutes, and speed may be changed for each transmission.

The classic approach to choice of speed has been to look at the frame error rate of the last transmission and choose a speed based on this. Anecdotal evidence suggests that this approach does not work very well, as there is a tendency to oscillate between speeds without stable convergence on an optimal speed. The Isode 2014 measurements suggest that ITV leads to error pattern variation such that two minutes is insufficient time to determine an optimal transmission rate for the next period based on error pattern and suggest that determining speed for the next two minutes of transmission based on performance of the previous two minutes is sub-optimal.

When considering ITV, transmission quality may be thought of as a wave of varying quality with periodic variation in the range of 10 seconds to a few minutes. The Isode 2014 measurements suggest that SNR values are a good indication of transmission quality and can be used to examine the "quality wave". The paper will look at two application strategies to operate in light of the characteristics of this wave. The first strategy is to pick a single setting that will be used for a number of minutes to optimize throughput, which might be thought of as "cutting through the wave". The second approach considered is to change parameters much more frequently to deal with varying conditions and to analyse how predictable variations are shorter term and if it would be viable to adapt quickly to conditions and "ride the wave". The goal of this analysis is to help inform a decision as to whether this approach would gain sufficient performance to justify the additional overheads and complexity of rapid parameter change.

SNR data from multiple measurements on three links is analysed to look at both of these approaches. Many modern applications, such as real time chat, have relatively low volumes of

data and a desire to optimize latency and these need to be used in conjunction with "bulk" applications where it is important to optimize throughput. The paper concludes by examining how the results can be used in support of this mix of applications.

1 INTERMEDIATE TERM VARIATION

Variations in HF Radio transmissions over a range of periods, has long been noted, for example Goodman [5] p268 refers to CCIR Reports 266-6 and 304-2. However, most HF analysis has been devoted to Rayleigh Fading and other variations in signal over periods of a few seconds, such as Doppler and multipath. Modem and waveform design has been focussed to address these short term variations, and channel simulation and testing of modem waveforms is based on short term variation (e.g., the CCIR family of models). "The Walnut Street Model of Ionospheric HF Radio Propagation" [1] provides a useful summary of variation of different periods and models intermediate variation based on 4 dB standard deviation and a 10s time constant.

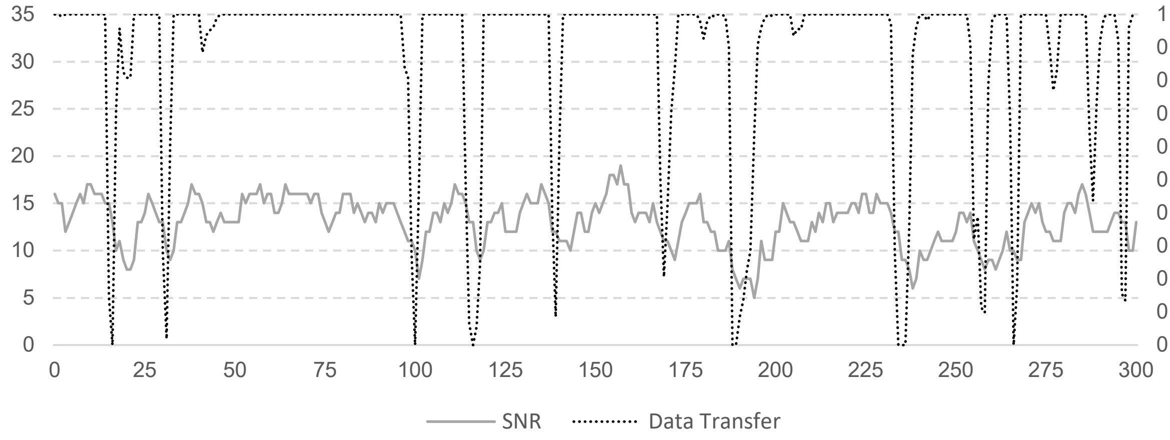
This modelling was refined by a group at Harris Corporation which broke down the variation into two basic elements: Intermediate Term Variation (ITV) and Long Term Variation [2]. This paper introduced the term ITV, which is used here. Isode in collaboration with Rockwell Collins made measurements of ITV in 2014 which fitted well with the Harris model and were reported on at HF Industries Association in September 2014 [3] and in a subsequent white paper [4]. Harris subsequently developed their model in [6].

2 THE EFFECT OF ITV ON APPLICATIONS

Typical HF data transmissions are from a few seconds (reflecting minimum lead times and block sizes in standard HF waveforms) to two minutes (reflecting the upper transmission bound in STANAG 5066 HF Link Layer [7]). ITV leads to significant variations over this timeframe, often showing changes in SNR of 15-20 dB. This can be seen from measurements in [4], comparing application throughput on a real link to CCIR simulation. Two graphs from that paper are included here.

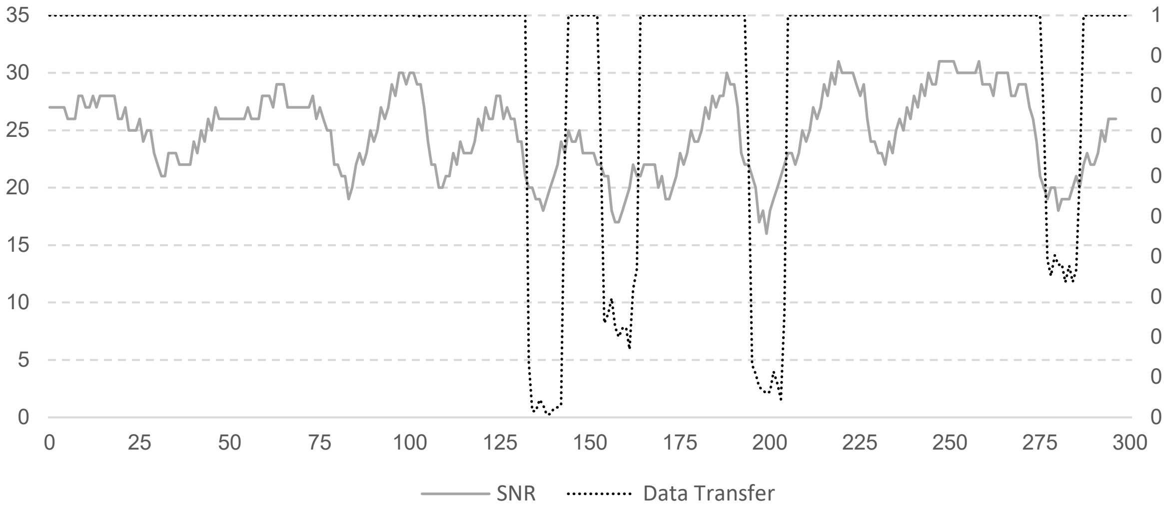
Figure 1 shows data loss over a link using CCIR Good characteristics, with data transfer showing 1.0 for no loss.

Figure 1: Data loss over a link with CCIR Good characteristics



The graph in Figure 2 shows data loss over a real link, with SNR reflecting ITV.

Figure 2: Data loss over a real link, reflecting ITV



It can be seen that the data loss is grouped into blocks, much more strongly than would be the case if the channel did not have ITV.

This paper looks to investigate more closely the impact of ITV on the applications running over HF and how such applications can best be optimized in light of ITV. Optimization for latency and throughput are both considered, with particular focus on optimization for throughput, which is the harder problem.

3 SNR BASED ANALYSIS

The application level is primarily concerned about whether data is valid or not. It is clear from the measurements in [4] that there is a very strong correlation between data loss and SNR. This is to be expected, as modem waveforms at a given speed will require a certain SNR to perform reliably. It might be argued that by definition SNR and data loss will be linked. A more interesting question is to consider how accurate the SNR reported by a modem is. This paper assumes a direct correlation between reported SNR and error rate.

For the modems Isode has access to, getting SNR information at about 1 second intervals is the smallest possible gap between measurements. SNR values in all the measurement runs taken are typically stable for a small number of seconds before changing. This suggests that the SNR reported by the modem is usefully measuring at ITV-relevant timeframe and is not being significantly impacted by changes of timeframe less than a second.

When considering data loss in an SNR vs waveform speed graph, modern waveforms will exhibit a “waterfall” characteristic, where they move rapidly from no data loss at a higher SNR to complete data loss at a lower SNR. The measurements are analysed by considering for each second whether or not data at a given speed and SNR for that second would be transferred. A simple binary model is used, with a fixed SNR level switching from good to bad. This is in line with the waterfall model. It also reflects that *any* error is likely to affect a block of link level data (requiring retransmission), so there is little practical difference at the application/link level between a few errors and a lot of errors in a short period.

This analysis is based on waveform block size (interleaver) being less that one second, so that each second is independent. A longer interleaver will reduce errors, but will also spread the impact over a longer period in the event of errors occurring.

4 MEASUREMENTS USED

This paper uses three sets of measurements. The first set was made by Isode in collaboration with Rockwell Collins and is described in detail in [4]. Rockwell Collins ran the tests over a mid-latitude channel between Cedar Rapids, Iowa and Las Cruces, New Mexico on 26-29th August 2014. This used Rockwell Collins RT-4800 WBHF Modems.

The second two sets were made by QinetiQ using a Harris 5710A modem to listen to HF Broadcast data in the UK. The first link was a good quality link of about 2,000 miles. The second link was a poor quality link of about 400 miles.

The results from the good UK (QinetiQ) link and the US (Rockwell Collins) link (also good) have many similarities and fit well with the ITV models described about. These are examined next. The poor quality UK link had significantly different characteristics and this is looked at separately.

5 GOOD LINK ANALYSIS

The six good quality measurement sets showed patterns of SNR variation with many common characteristics. Figure 3 shows the overall picture for the second US link run.

Figure 3: SNR for second US link run

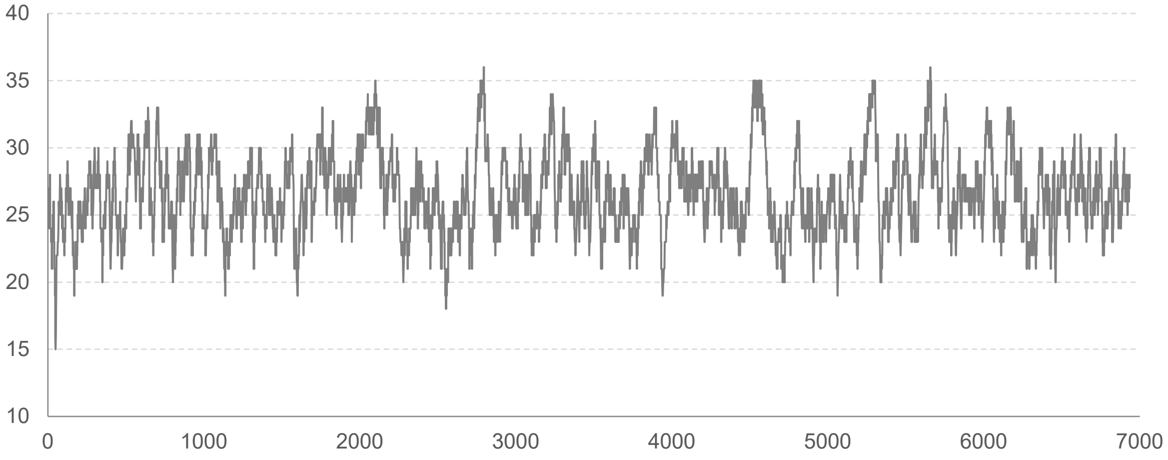


Figure 4 shows an extract to show a typical five-minute segment.

Figure 4: 5-minute SNR extract from second US link run

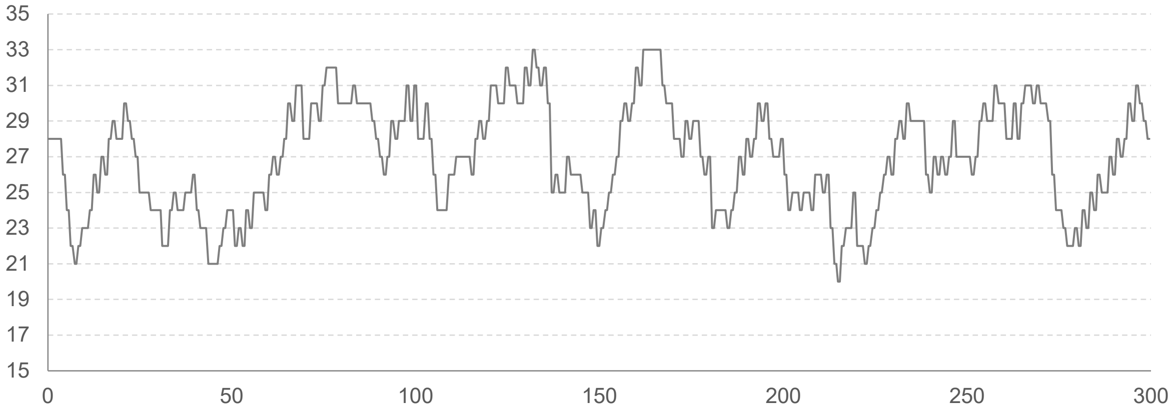


Figure 5 shows the SNR for the second UK link run. Note that the SNR measurements are clipped at 23, and it seems likely that the actual SNR was better. The modem was idle at times (no signal) and this is recorded as SNR of -20.

Figure 5: SNR for second UK link run

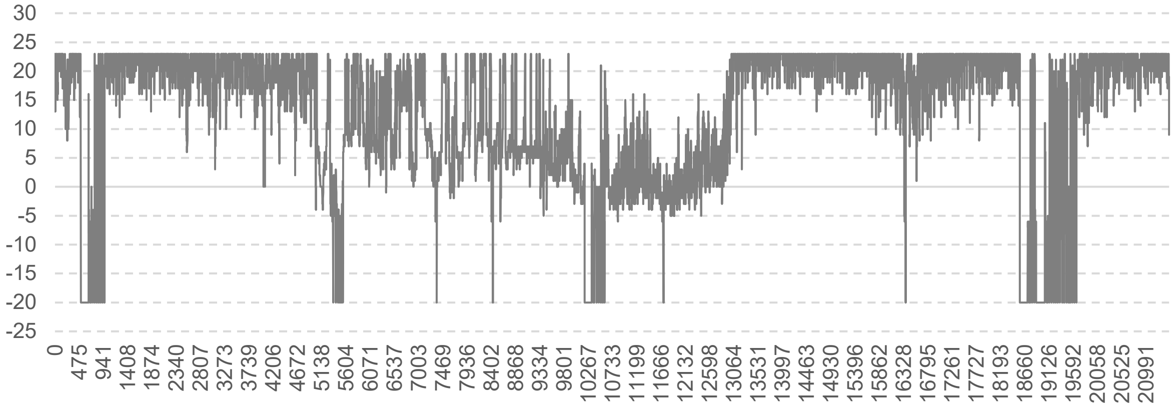
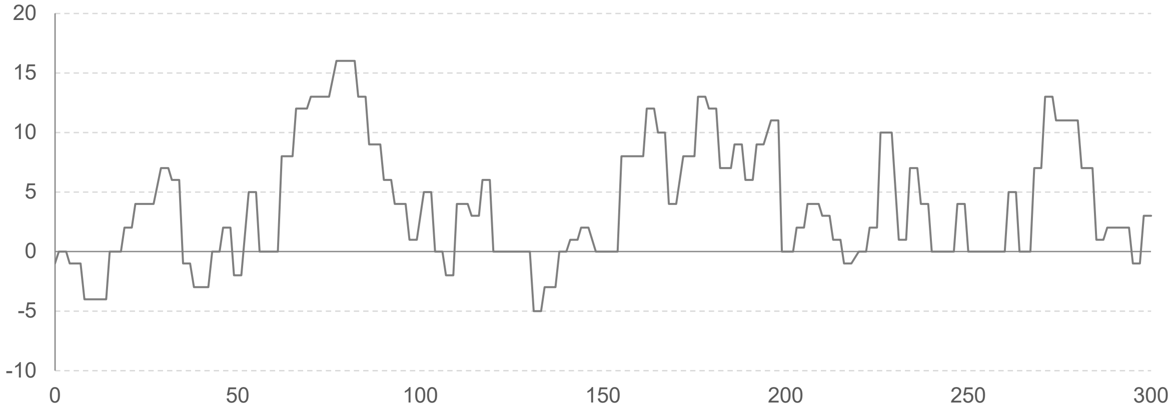


Figure 6 is an extract to show a typical five-minute segment.

Figure 6: 5-minute SNR extract from second UK link run



The broad SNR spread in these two graphs and broad style of SNR variation is similar at both full run and detailed level. The UK link runs show much higher longer term variation, including periods of no reception. In part, this is because the UK runs were longer.

The SNR variation is in line with the Harris models [2], [6] with strong variation on timeframe of around 10 seconds (just over 10dB for US link and 15-20dB for UK link) coupled with weaker variation over periods of a few minutes and other longer term variations.

A basic analysis was performed for each run, to choose for each second, the fastest speed that would successfully transmit and to calculate performance based on this. This is the “perfect” algorithm, based on a priori knowledge of the SNR. This gives a baseline against which to measure other approaches. The base characteristics of each run are shown in Table 1.

Table 1: Summary of run characteristics

Link	Duration of Run	Perfect Throughput
US 1 (Rockwell Collins)	59 minutes	11,918 bps
US 2 (Rockwell Collins)	59 minutes	10,494 bps
UK 1 (QinetiQ)	231 minutes	6,880 bps
UK 2 (QinetiQ)	357 minutes	4,974 bps
UK 3 (QinetiQ)	411 minutes	4,411 bps
UK 4 (QinetiQ)	168 minutes	6,872 bps

5.1 FIXED SPEED PERFORMANCE

The first analysis, based on consideration of each (approx.) one-second period using the waterfall analysis described above, is to look at performance for transmission at fixed speeds. The analysis in table 2 shows first the percentage of data that was transferred and second percentage of the "perfect" throughput. The best throughout is highlighted for each run.

Table 2: Fixed Speed Performance

Link	US 1	US 2	UK 1	UK 2	UK 3	UK 4
75	100%/0%	100%/0%	99%/1%	93%/1%	90%/1%	99%/1%
150	100%/1%	100%/1%	98%/2%	89%/2%	81%/2%	99%/2%
300	100%/5%	100%/2%	98%/4%	84%/5%	75%/5%	99%/4%
600	100%/5%	100%/5%	97%/8%	78%/9%	70%/9%	98%/8%
1200	100%/10%	100%/11%	97%/16%	74%/18%	68%/18%	98%/17%
2400	100%/20%	100%/22%	96%/33%	70%/33%	64%/35%	97%/33%
3200	100%/26%	100%/30%	91%/42%	66%/42%	59%/43%	95%/44%
4800	100%/40%	100%/45%	88%/61%	62%/60%	54%/59%	91%/64%
6400	100%/53%	99%/60%	80%/75%	56%/72%	47%69%	80%/74%
8000	99%/67%	99%/75%	69%/80%	46%/75%	40%/73%	63%/73%
9600	98%/79%	86%/79%	0%/0%	0%/0%	0%/0%	0%/0%
12000	76%/77%	36%/41%	0%/0%	0%/0%	0%/0%	0%/0%
16000	12%/17%	6%/9%	0%/0%	0%/0%	0%/0%	0%/0%

It can be seen that for slower speeds, data loss is low. For the US link, utilization is 100% up to 4800 bps. For the UK link, there were some periods (1% of each run) when no data was received and some places where data throughput dropped significantly.

In all cases, one fixed speed generated good throughput, reaching a significant percentage of the perfect throughput (73% - 80%). Use of fixed speed could be a sensible strategy, particularly where, as in the US link, no significant drops in speed occurred. For the UK link, a variable speed strategy would give the benefit of providing some data transmission in periods where link quality dropped.

5.2 PERFECT AND ACHIEVABLE THROUGHPUT

There are two measurements used for comparison in the subsequent sections:

1. **Perfect** throughput. As noted above, this is calculated by looking at each second and picks the best speed for each second.
2. **Achievable** throughput. Where fixed speed transmissions are made for a given time (e.g., 120 seconds) perfect throughput would not be possible. The "achievable" calculation looks at each transmission slot, and chooses the speed for that slot which achieves highest throughput.

5.3 FRAME ERROR RATE (FER) vs SNR

Two variable speed strategies are now considered. The following analysis is on the basis of two-minute data transmissions and analysis of the previous two minutes of traffic. This is the value typically used for bulk transfers over STANAG 5066.

The first approach is the Trinder/Gillespie (TG) [7] algorithm, which was an enhancement of the earlier Trinder/Brown algorithm based on practical measurements. This algorithm increases speed by a single step if Frame Error Rate (FER) is less than 20% and decreases speed by one step if FER is greater than 50%. The analysis here used percentage of errors, which is a reasonable approximation and will reflect Trinder/Gillespie exactly if frame length is one second.

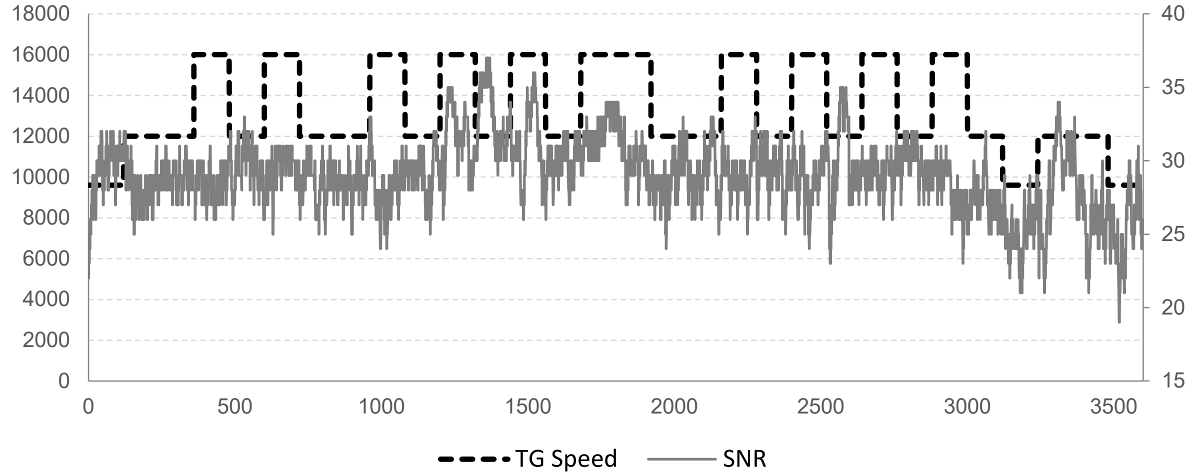
The second approach is to average SNR in dB measured over the period using a simple mean. This SNR is then compared against a table of SNR vs Speed. For this analysis, the same table is used as the one used for the "waterfall decision" on each second of data transmitted. For both Trinder/Gilliespie and SNR, comparison is made against perfect throughput and "achievable" throughput, which reflects the throughput achievable if the best choice is made for each speed. The results are shown in Table 3.

Table 3: FER vs SNR Comparison

Link	FER (perfect)	FER (achievable)	SNR (perfect)	SNR (achievable)
US 1	57%	68%	79%	95%
US 2	59%	76%	72%	92%
UK 1	53%	61%	81%	94%
UK 2	48%	60%	71%	88%
UK 3	48%	59%	71%	88%
UK 4	59%	74%	71%	89%

The results with SNR are superior to the FER based approach of Trinder/Gillespie. In all cases around 90% of the achievable throughput is reached, which seems a good result. This is similar too (in some cases higher and some lower) than the best results from fixed speed. The paper considers later how these numbers might be improved.

Figure 7: Trinder/Gillespie speeds and SNR for first US link run



This graph in Figure 7 shows a number of things:

1. At the end for the run, the speed usefully adapts to conditions getting poorer.
2. There is an oscillation of speeds, which has been anecdotally noted as a problem with this approach.
3. Transmitting at 12000 is a good choice, but going faster at 16000 is generally a poorer choice, and the algorithm is being too optimistic and making poor choices.

It seems likely that an FER based algorithm could be tuned to give better performance than the standard Trinder/Gillespie algorithm measured here. However, because the SNR based approach delivers better performance, this is the approach investigated further in this paper.

5.4 OPTIMIZING TRANSMISSION LENGTH

The performance for various lengths of data transmission is now considered. For each transmission length, average SNR of prior transmission is used to determine speed of the next transmission. Various lengths of SNR analysis were used and the results in this section reflect the best result achieved. Table 4 shows performance measurements as a percentage of perfect performance.

Table 4: Transmission performance for different transmission length as % perfect throughput

Link	**120s**	**60s**	**30s**	**20s**	**10s**	**5s**
US 1	79%	80%	83%	82%	84%	85%
US 2	77%	77%	76%	76%	73%	78%
UK 1	81%	82%	81%	81%	82%	83%
UK 2	71%	73%	74%	75%	76%	76%
UK 3	73%	74%	75%	76%	77%	82%
UK 4	73%	74%	75%	76%	78%	78%

It can be seen that performance is similar for different transmission lengths. In most cases, performance improves slightly as transmission length decreases with a 1-9% improvement range when going from 120 seconds (2 minutes) down to 5 seconds.

Although there is a small performance increase with shorter transmissions, this will not be sufficient to compensate for the overhead of turnaround time in current systems. So in current systems, 120 second transmissions will be best to optimize performance. If turnaround times can be minimized, it is possible that future systems will be able to take advantage of the very small performance increase seen with shorter transmissions.

Table 5 measures throughput in terms of achievable throughput for each transmission length (i.e., if the algorithm picks best speed for each segment). It can be seen that for longer transmission, higher percentages are achieved, reflecting the relatively stable nature of the links and that it is harder to predict shorter term fluctuations.

Table 5: Transmission performance for different transmission lengths as % achievable output

Link	**120s**	**60s**	**30s**	**20s**	**10s**	**5s**
US 1	95%	93%	93%	90%	91%	90%
US 2	98%	94%	89%	88%	81%	84%
UK 1	94%	90%	91%	91%	88%	86%
UK 2	88%	89%	87%	86%	84%	80%
UK 3	91%	89%	88%	87%	84%	78%
UK 4	91%	90%	89%	88%	86%	83%

5.5 OPTIMIZING SNR MEASUREMENT PERIOD

In order to decide on the speed to transmit for the next transmission, the SNR for a period of time before transmission is measured and averaged. The performance achieved based on the length of time over which SNR was averaged is shown in the Table 6. This is the percentage of achievable throughput for 120 second transmissions, looking at the effect of analysing SNR for a different period prior to transmission.

Table 6: Transmission performance based on length of SNR time used in calculation

Link	**10s**	**30s**	**60s**	**120s**	**240s**	**480s**
US 1	90%	95%	91%	95%	93%	91%
US 2	86%	85%	88%	92%	98%	97%
UK 1	85%	91%	90%	94%	92%	92%
UK 2	85%	88%	88%	88%	86%	83%
UK 3	87%	90%	90%	88%	86%	81%
UK 4	83%	91%	91%	89%	91%	91%

Notes on the analysis:

- 10 seconds is insufficient, but in most case 30 – 480 seconds will give a reasonable result.
- There appears to be a trade-off between getting “most recent” information and a better average using more data. From these numbers, a choice in the range 60-240 seconds would seem sensible.

- In a real system, a receiver will be constrained as to when it can make measurements. In a multi-node system or in a two node system making 120 second transmissions in both directions, SNR data is going to be older and there will also be delays in communicating this data (or recommendations derived from this data) to the sender. This suggests that in practice it will be more useful to take a longer average, as SNR data very close to the current time will not be available.

5.6 RIDING THE WAVE

The paper has so far considered approaches that lead to long transmissions and use of average SNR to set best values for longer transmissions. We now consider the "riding the wave" approach and the possibility of adapting more rapidly to SNR.

Table 7 shows analysis based on five second transmissions, with results measured as a percentage of achievable throughput. The first column shows the results based on measuring the previous 5 seconds of SNR. The second column looks at the best result achieved and the third column looks at the SNR period measurement that achieved this.

Table 7: Analysis of 5-second transmissions

Link	5 Second %	Best %	Best Time
US 1	86%	90%	10-20 seconds
US 2	82%	84%	10 seconds
UK 1	80%	86%	25-30 seconds
UK 2	78%	81%	20-25 seconds
UK 3	78%	82%	25-30 seconds
UK 4	78%	83%	20-25 seconds

These results show very clearly that analysing based on the previous five seconds does not lead to the best result, and that a longer average gives higher performance. The significance of this is that it shows clearly that to "ride the wave" 5 second granularity is insufficient.

Table 8 shows as percentage of perfect throughput achieved based on looking at the single second intervals just before the second.

Table 8: Analysis of 1-second transmissions

Link	Last Second	Previous Second	Second Before
US 1	93%	87%	87%
US 2	92%	86%	84%
UK 1	94%	89%	84%
UK 2	93%	87%	80%
UK 3	93%	87%	81%
UK 4	93%	86%	79%

These numbers show that with single second granularity, that there is very strong correlation with the previous seconds. If it were possible to know the SNR of the previous second, greater than 90% of perfect throughput appears achievable.

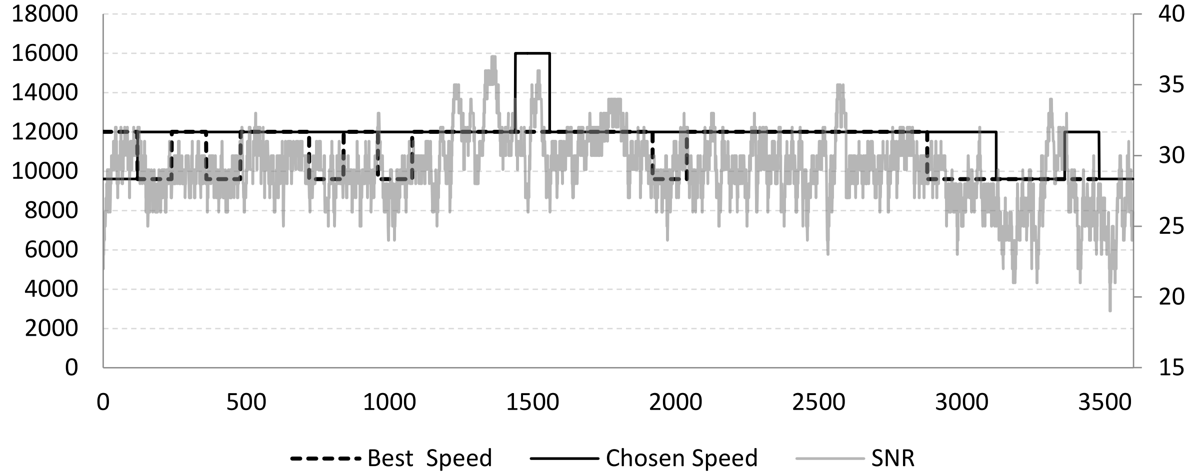
In a duplex setup, it might be possible to transfer SNR information with a second or two latency. This still gives good results, although for some of the UK runs, two seconds out gives performance comparable to fixed speed.

These numbers show that in theory a good performance result could be achieved, perhaps gaining 10% over fixed speed. This would appear difficult to achieve in practice. Given that the gains are not large; it is not clear that it is useful to attempt this.

5.7 TUNING SNR CHOICE

This section gives consideration as to how the SNR choice might be improved. The following graph looks at choices made in the first US run. The dashed black line indicates the best (achievable) speed for each two-minute segment and the solid black line the speed actually chosen. The choices made achieved 95% of the achievable throughput.

Figure 8: Comparison of Best Speed and Chosen Speed



It can be seen that the two “incorrect” upward jumps seem to be reactions to short improvements in SNR. These could be removed by increasing the period of SNR averaging, but this would make the algorithm less reactive to real changes. Several of the “incorrect” decisions not to slow down do not seem in any way predictable.

Analysis of this information in this manner is not showing any immediately obvious changes that should be made. We suspect that the algorithm could be tuned and improved. Possibilities include:

- Investigate other methods of averaging of SNR as alternative to simple mean.
- Weighting SNR data, to more highly favour recent data
- Modifying the exact SNR/Speed change points to be more or less aggressive.
- Including recent SNR trend in the algorithm

Significantly larger data sets would be needed to test such changes.

6 POOR LINK ANALYSIS

Results from the second UK link, which was informally characterised as a poor link, are quite different to the previous results and so are described separately as the analysis and considerations are different. Figure 9 shows the first run of three.

Figure 9: Poor link SNR, first run

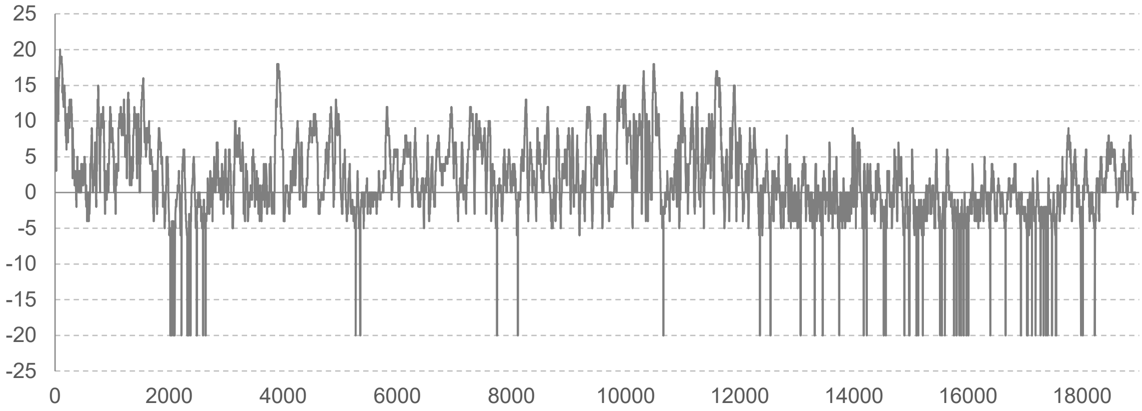
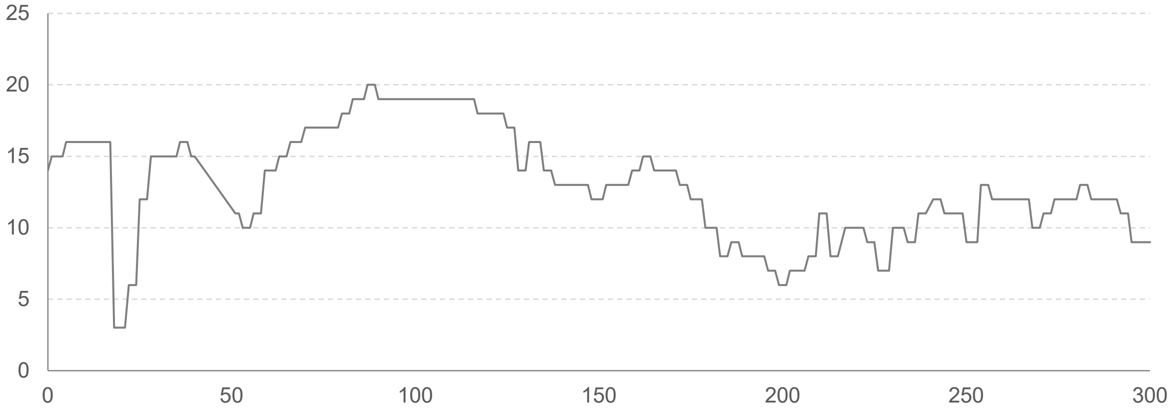


Figure 10 shows a five-minute segment.

Figure 10: Five-minute SNR extract from Poor Link, first run



The graphs shown in Figures 9 and 10 look quite a bit different to the earlier ones shown in Figures 3-6. There is less fluctuation in SNR of order ten seconds (a key characteristic of the Harris ITV models seen in the earlier graphs) and the longer fluctuation is not around a fixed level, but moves much more. This suggests a much strong variation in range 1-10 minutes, which is brought out by subsequent analysis.

We believe that this data does not fit the Harris models [2], [6] and that there is a class or classes of link characteristic that need a new model or an extension to the proposed models.

Table 9: Summary of Poor Link runs

Link	**Duration of Run**	**Perfect Throughput**
Poor 1	315 minutes	789 bps
Poor 2	403 minutes	744 bps
Poor 3	335 minutes	181 bps

It can be seen that the links are poor quality, and the third run was particularly poor. Analysis on these links is now provided as for the good links.

6.1 FIXED SPEED PERFORMANCE

Table 10: Fixed Speed Performance for Poor Link

Link	Poor 1	Poor 2	Poor 3
75	98%/9%	99%/9%	80%/33%
150	82%/15%	85%/17%	42%/34%
300	53%/20%	53%/21%	14%/24%
600	34%/25%	33%/26%	6%/20%
1200	23%/36%	22%/35%	3%/21%
2400	15%/47%	14%/46%	1%/15%
3200	9%/37%	8%/34%	0%/2%
4800	3%/20%	2%/17%	0%/0%
6400	0%/0%	0%/0%	0%/0%
8000	0%/0%	0%/0%	0%/0%
9600	0%/0%	0%/0%	0%/0%
12000	0%/0%	0%/0%	0%/0%
16000	0%/0%	0%/0%	0%/0%

As well as the links being poorer, the level of variation means that fixed speed achieves a much smaller percentage of the perfect throughput. The best achieves is 47%, in contrast with around 80% for the good links.

6.2 FRAME ERROR RATE (FER) vs SNR

Table 11: FER vs SNR for Poor Link with 120-second transmissions

Link	FER (perfect)	FER (achievable)	SNR (perfect)	SNR (achievable)
Poor 1	25%	40%	30%	47%
Poor 2	29%	49%	32%	51%
Poor 3	35%	59%	42%	70%

The first set of FER vs SNR calculations show in Table 11 uses the same parameters as for the good links table, with 120 second transmission and measurement periods. SNR gives the better results, although the level of improvement is less marked.

Table 12: FER vs SNR for Poor Link with 10-second transmissions

Link	FER (perfect)	FER (achievable)	SNR (perfect)	SNR (achievable)
Poor 1	47%	54%	63%	72%
Poor 2	47%	54%	63%	72%
Poor 3	47%	61%	59%	76%

Table 12 shows the same analysis, but using the previous ten seconds rather than 120 seconds. Here both FER and SNR approaches better performance, with SNR giving significantly better throughput than fixed speed. Best transmit length is considered in the next section.

6.3 OPTIMIZING TRANSMISSION LENGTH

Table 13: Performance for different transmission lengths on Poor Link

Link	120s	60s	30s	20s	10s	5s
Poor 1	30%	40%	50%	55%	63%	72%
Poor 2	32%	40%	46%	49%	56%	65%
Poor 3	46%	51%	56%	55%	59%	64%

Table 13 shows best throughput for a range of transmission lengths, with performance as a percentage of perfect. This table is in marked contrast to the good links. Here, the very short transmissions give significant improvement in performance. There is significant potential for performance gain by shortening transmission lengths. This gain needs to be considered in context of the overhead of turnaround, but there seems potential to improve performance with shorter transmissions.

6.4 OPTIMIZING SNR PERIOD

The following tables show the effect of varying period over which the SNR is analysed for three different throughput speeds, with percent of perfect throughput shown.

Table 14: Throughput for 120-second transmission and different SNR calculation period

Link	10s	30s	60s	120s	240s	480s
Poor 1	30%	29%	28%	30%	27%	29%
Poor 2	34%	33%	32%	32%	29%	25%
Poor 3	46%	44%	43%	42%	39%	39%

Table 14 is for 120-second transmission intervals. It can be seen the measurement period does not have a significant effect on performance.

Table 15: Throughput for 10-second transmission and different SNR calculation period

Link	10s	30s	60s	100s
Poor 1	63%	50%	43%	47%
Poor 2	56%	48%	42%	45%
Poor 3	59%	55%	50%	46%

Table 16: Throughput for 5-second transmission and different SNR calculation period

Link	5s	10s	20s	30s	50s
Poor 1	72%	63%	58%	53%	47%
Poor 2	65%	60%	54%	50%	46%
Poor 3	64%	62%	59%	57%	52%

Tables 15 and 16 show that averaging over a short period in conjunction with short transmissions leads to significantly better performance. If you use longer times, the effect is broadly to align to the long term average performance (of around 40-45% perfect). Because there is so much variation of SNR in 1-10 minute time frame, this is the best that can be achieved with longer transmissions and averaging measurement.

Shorter measurements and transmissions allow the speed to be better followed and to gain performance. These gains would need to be traded off against the overhead of turnarounds. A concern for aggressively optimizing performance for a poor quality link is that there is risk of losing synchronization. The potential gains from shorter transmissions shown here may be difficult to achieve in practice.

A similar analysis can be performed for single second transfer, as was done for the good links.

Table 17: Throughput analysis for 1-second transmission

Link	**Last Second**	**Prev**	**Prev 2**
Poor 1	92%	85%	78%
Poor 2	90%	81%	71%
Poor 3	83%	74%	66%

Single second correlation is strong and if transitions could be made that rapidly, there is potential for significant performance improvements, although it may not be practical to do this.

7 IMPLICATIONS FOR LINK LAYER AND APPLICATIONS

In order to operate modern applications over HF Radio, a link layer is needed that will provide error free data transfer and multiplexing between applications. STANAG 5066 [7] is a good option to achieve this. Detailed considerations of optimizing applications for HF are given in Isode White Paper [9] and HFIA Presentation [10].

When starting an HF transmission, the sender needs to make a choice of speed and other parameters for the period of that transmission. Information from the receiver is needed to help make that choice, and mechanisms to achieve this are discussed in [9]. To take advantage of the approaches discussed in this paper, such communication is vital.

If a sender chooses to optimize for latency, the key decision is to transmit at a “safe” slow speed, which may be coupled with sending key data multiple times, as described in [3] and [4]. The receiver can generally recommend a safe speed, and also indicate likelihood of loss (even in the UK good transmissions, there were periods where no transfer was possible at any speed).

The strategy to optimize for throughput is more complex. The measurements in this paper have shown two classes of link characteristics that need different handling at the application level. These characteristics may be known a priori, but if they are not known, the HF receiver can analyse SNR over a period to determine if a link fits one of these characteristics.

For a good link (following the characteristics of the first two links), it seems clear that 120s transmissions are desirable. This should be used with long interleavers as discussed in [4]. SNR measurements over a period of 1-2 minutes.

A simple average SNR calculation to choose transmission speed will work well. It is possible that superior algorithms could be developed, as discussed in the paper.

For a poor link, the same strategy could be followed, which would lead to robust performance with conservative numbers. If short turnaround times can be achieved, it seems possible that performance gains can be achieved by using shorter transmissions. The viability of this needs to be tested and demonstrated.

The paper has shown that if it was possible to change speed and parameters to adapt to SNR with timeframe of a second or so, performance improvements of 10% or so may be achieved. It seems likely that this is not practical to achieve, and the relatively modest performance gain does not justify work on this.

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REFERENCES

[1] Eric E Johnson, *The Walnut Street Model of Ionospheric HF Radio Propagation*, New Mexico State University, May 1997 http://goo.gl/4bT8ew (9 May 2016)

[2] W.N. Furman, and E. Koski, *A Model of Ionospheric Channel Quality Variation for HF Communications System Analysis and Evaluation*, Proceedings of the 12th International Ionospheric Effects Symposium (IES2008) 2008, Alexandria, VA, May 2008.

[3] Jim Peters, Isode Ltd., *Analysis of OTA Measurements*, Presentation to HFIA, September 2014 http://goo.gl/xKygJa (9 May 2016)

[4] Isode, *Measurements of Skywave HF Radio Intermediate Term Variation and Implications for Optimizing Link Performance*, Whitepaper, December 2014, http://goo.gl/7XGu2Y (9 May 2016).

[5] J. Goodman, *HF Communications Science and Technology*, Van Nostrand Reinhold, New York, NY, 1992.

[6] W.N. Furman, and E. Koski, *Standardization of an intermediate duration HF channel variation mode*l, The Institution of Engineering and Technology 11th International Conference on Ionospheric radio Systems and Techniques, 2009

[7] STANAG 5506 Edition 3. *Profile for High Frequency (HF) Radio Data Communications*, December 2010, Web http://goo.gl/jaczAh (10 May 2016)

[8] S.E. Trinder and A.F.R Gillespie, *Optimization of the STANAG 5066 ARQ Protocol to Support High Data Rate HF Communication*, Proceedings of IEEE Military Communications Conference (MILCOM) 2001, Washington DC, October 2001

[9] Isode, Optimizing STANAG 5066 Parameter Settings for HF & WBHF, White Paper, April 2014, http://goo.gl/p5u82N (11 May 2016)

[10] Steve Kille and Jim Peters, Optimizing STANAG 5066 Parameter Settings for HF & WBHF, Presentation to HFIA, March 2014, http://goo.gl/l9hsC5 (11 May 2016)