University of Salford MANCHESTER

This report uses Chirp protocols as of 2017, which have been superseded by later advancements.

For updated performance data, please contact Chirp directly at info@chirp.io

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TEST REPORT No : 3567 **DATE OF ISSUE : 14/12/2017**

CHIRP DECODER:

INFLUENCE OF NOISE AND REVERBERATION

CLIENT:	Chirp WeWork, 3 Waterhouse Square 138 Holborn, London, EC1N 2SN
JOB NUMBER:	ACOUS/03567
TEST SAMPLE:	Chirp encoder/decoder: Standard (2017) and Ultrasonic (2017) protocols
DATE OF TESTS:	26th October to 1st November 2017

Signed:……James F. Massaglia……

James Massaglia

Research Assistant

Approved:……Trevor Cox……

Prof. Trevor Cox

Contents

1 Test Method

1.1 Setup and test signals

The test signals consisted of chirps of two different protocols (Standard (2017) and Ultrasonic (2017)). The following information for each protocol was provided by the client:

- **Standard (2017)**:
    - Frequency range: 1.76kHz to 10.5kHz
    - Payload size: 50 bits
    - Duration: 1.744s
    - Data rate: 28.7bps
- **Ultrasonic (2017)**:
    - Frequency range: 18.2kHz to 20.12kHz
    - Payload size: 32 bits
    - Duration: 1.44s
    - Data rate: 22.2bps

In all tests, the test signals were sent from and received by a Macbook laptop with an M-Audio external sound card. The signal was transmitted through a loudspeaker (Genelec 8030A) and received through a measurement microphone (B&K 4165 microphone, with a B&K 2619 preamp through a B&K 2610 measuring amplifier) and decoded. A Python script provided by the client (chirp-auto-tester.py) was used to send and receive 100 chirp signals in each test, giving the number of decoding successes and failures upon completion.

Two interference conditions were tested:

- **noise**
- **reverberation**

For each interference condition, the following metrics were obtained:

- **Receive rate:** ratio of chirps received and successfully decoded to total number of chirps sent (1=all chirps detected and successfully decoded, 0=all decode failures and/or non-detections)

- **1% Error Threshold**: value of SNR or RT at which 99% receive rate (1% decode failure and/or non-detection) is expected

1.2 Noise interference

The noise interference tests were carried out in the listening room of the Salford University acoustic research centre, with dimensions: 6.6 m × 5.8 m × 2.8 m, and average reverberation time: 0.37 s (full reverberation time measurements in Section 2.3.4).

Interfering noise was introduced though a separate loudspeaker (Genelec 8030A) for each test. The receiver microphone was placed at 2m distance from both speakers. A sound level meter (Svantek 957) was positioned at the same location as the receiver microphone (1cm apart) to measure the octave band sound levels produced by the test signals and the interfering noise. The chirp signal level was measured by emitting a continuous stream of chirps for each protocol (using the client provided Python script chirp-play.py) and carrying out a linear 30 second L_{eq} (average sound pressure level) at the receiver position. Similarly, the noise levels were measured with a 30 second L_{eq} for the highest amplitude setting, in order to obtain the SNR, and are shown in the Section 2.2.4 in octave bands. The background noise in the listening room was measured before testing to ensure the signal levels were at least 15dB above background; the background noise levels are also shown in the Section 2.2.4.

The three interfering noise types are given below:

1. **Traffic:** noise shaped based on the average spectrum of traffic noise given in BS EN ISO 717-1 (C_{tr} reference spectrum); spectrum shown in Figure 1, below
2. **Speech:** samples from four speakers (2 male, 2 female) mixed together from speech recorded in the University of Salford anechoic chamber
3. **Music:** a sample from Get Lucky by Daft Punk (start time: 1m06s; end time: 1m31s)

In each test, the samples were played on a continuous loop while 100 chirps were sent and received over a period of approximately 3:40m per test. In each successive test, the interfering noise level was reduced in steps until a 100% chirp receive rate was achieved. Additional interfering noise levels were also tested in order to verify repeatability and reduce the 95% confidence intervals for 1% error threshold estimation.

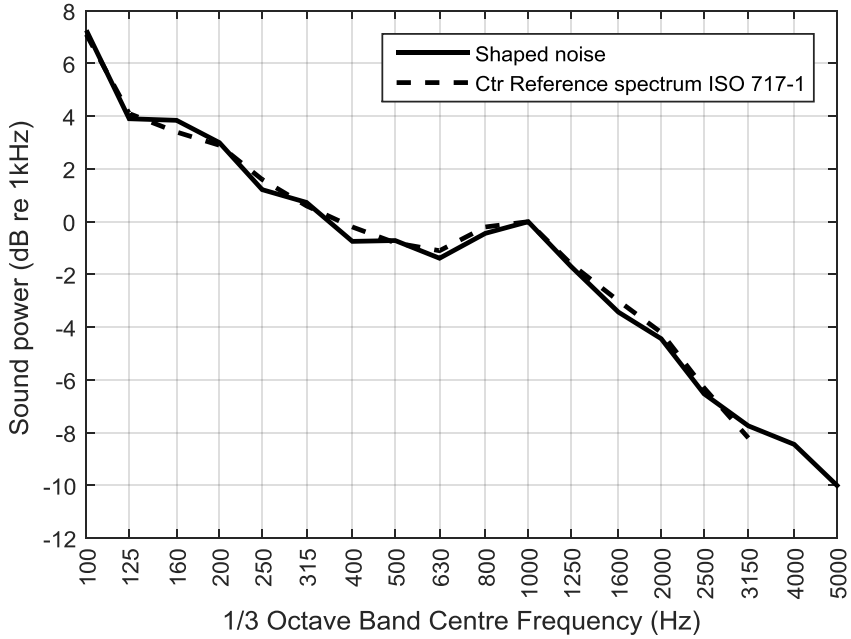

Figure 1: Traffic-shaped noise spectrum

1.3 Reverberation time interference

Reverberation time interference tests were carried out in the following spaces:

1. Listening room; volume: 107m^3
2. Maxwell lower hall
3. Large reverberation chamber (laboratory transmission suite receiver room); volume: 220 m^3
4. Small reverberation chamber: empty and with varying amounts of absorption, labelled “Absorption 1, 2, 3, 4, 5”; volume: 48 m^3

In all reverberation tests, transmitter loudspeaker and receiver microphone were positioned 3 m apart and over 1 m away from any room surface. The reverberation time was measured at the location of the receiver microphone using the interrupted noise method, averaged over 5 measurements using the Svantek 957 sound level meter and a pink noise source played from the transmitter speaker. For the small reverberation room tests, the reverberation time was gradually reduced by introducing absorptive foam panels into the room until the chirp receive rate was 100% over 5 trials; this allowed estimation of a 1% error threshold for reverberation time for the Standard (2017) protocol. The background noise was measured to ensure it was at least 15dB below the signal levels.

2 Results

The results here presented relate only to the items tested and described in this report.

2.1 Summary

This section is a presentation of key results requested by the client. Full results including confidence intervals are to be found in the next sections.

2.1.1 Noise interference

		Best case	Worst case
Standard (2017) protocol	**Interference**	Traffic-shaped noise	Speech
	Result	99% packets received with SNR of **-9.02 dB** in chirp frequency range (**-24.90 dB** broadband SNR)	99% packets received with SNR of **+3.27 dB** in chirp frequency range (**-10.29 dB** broadband SNR)
Ultrasonic (2017) protocol	**Interference**	Traffic-shaped noise	Music
	Result	99% packets received with SNR of **-12.51 dB** in chirp frequency range (**-48.86 dB** broadband SNR)	99% packets received with SNR of **-6.06 dB** in chirp frequency range (**-39.36 dB** broadband SNR)

Table 1: Summary of noise interference results

2.1.2 Reverberation time interference

	Result
Standard (2017) protocol	99% packets received with reverberation time of **0.80 seconds** in the chirp frequency range (**2.85 seconds** broadband reverberation time)
Ultrasonic (2017) protocol	100% packets received in all reverberant conditions - broadband reverberation time up to **5.95 seconds**

Table 2: Summary of reverberation time results

2.2 Signal-to-noise ratio

2.2.1 1% Error Threshold

The following tables show the estimated 1% error threshold from a 2nd order polynomial fit of SNR and receive rate data (full data in the next section; best-fit curves in the Appendix). Only points around the 99% receive threshold were included as indicated in Figure 6 (Standard (2017) protocol) and Figure 7 (Ultrasonic (2017) protocol). The SNR broadband values and over the signal ranges (2-8kHz octave bands for Standard (2017) protocol and 16kHz octave band for Ultrasonic (2017) protocol) are shown.

		1% Error Threshold [dB]		
		Traffic	**Music**	**Speech**
Standard (2017) Protocol	**SNR (2-8kHz)**	-9.02 ± 0.12	1.02 ± 0.03	3.26 ± 0.03
	Broadband SNR	-24.90 ± 0.04	-14.94 ± 0.03	-10.29 ± 0.03
Ultrasonic (2017) Protocol	**SNR (16kHz)**	-12.51 ± 0.03	-6.06 ± 0.03	-11.73 ± 0.04
	Broadband SNR	-48.86 ± 0.03	-39.36 ± 0.03	-45.94 ± 0.04

Table 3: 1% Error Threshold SNR for different interfering noises with 95% confidence intervals

2.2.2 Plots of SNR vs receive rate

The following graphs show the receive rate (0-1) for given SNR (broadband and in chirp signal octave bands). Sigmoid best-fit curves are also shown (details on the sigmoid curve fitting can be found in the Appendix).

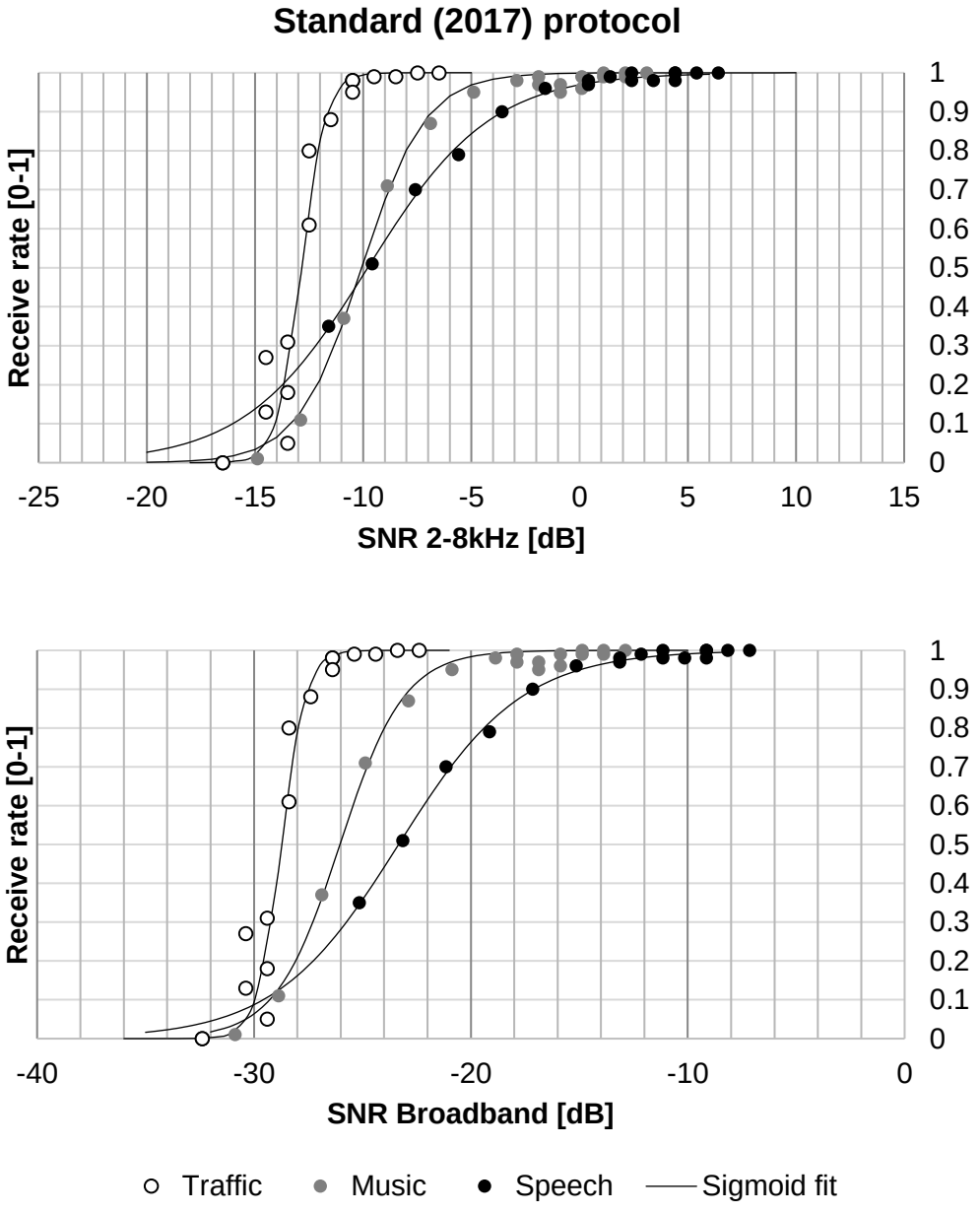

Figure 2: Interfering noise SNR (broadband and signal band) vs receive rate of standard protocol chirps; showing sigmoid curve fit

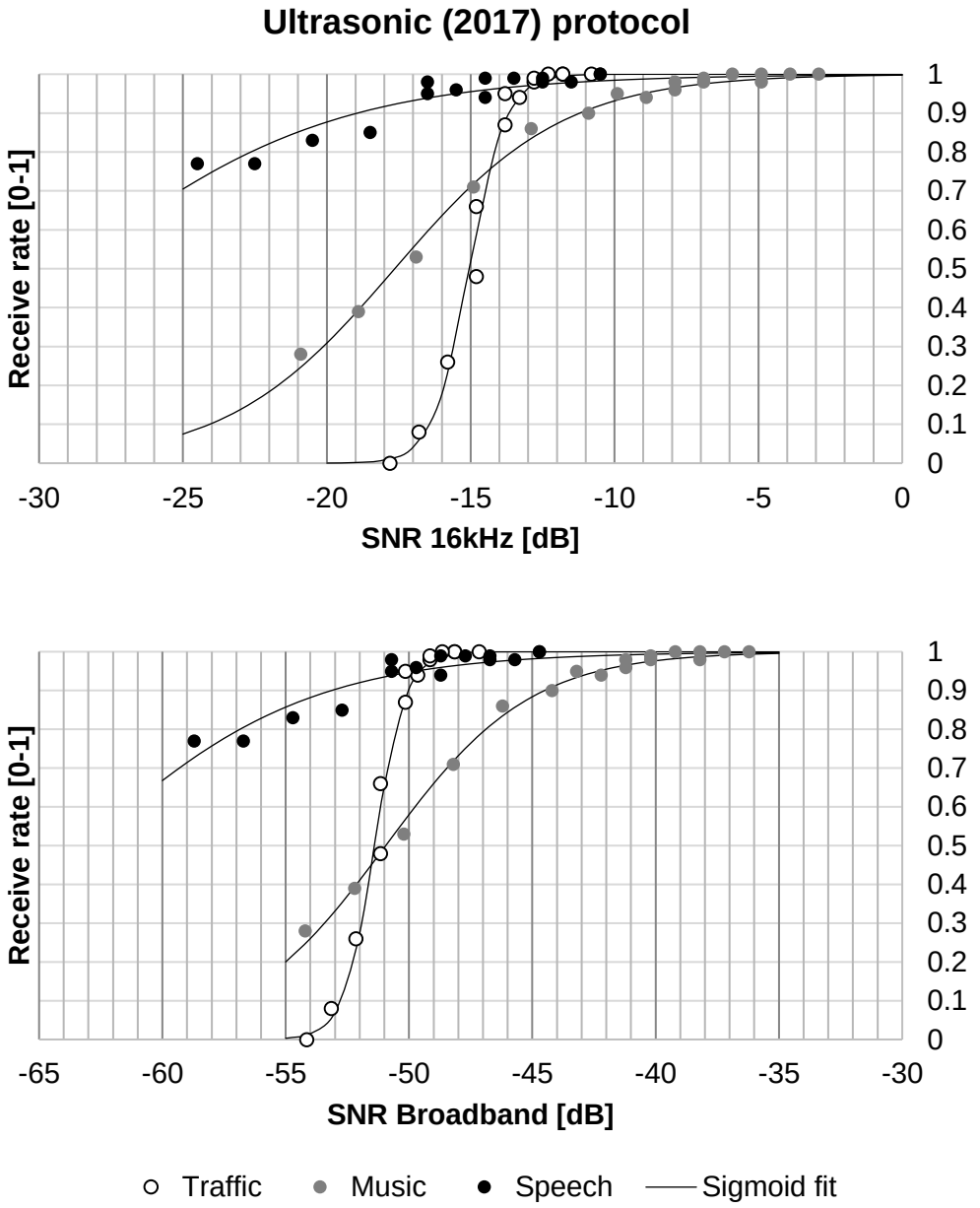

Figure 3: Interfering noise SNR (broadband and signal band) vs receive rate of Ultrasonic (2017) protocol chirps, showing sigmoid curve fit

2.2.3 Tabulated results

Standard (2017) protocol								
Traffic			**Music**			**Speech**		
SNR (2-8kHz)	**Broadb. SNR**	**Rec. Rate**	**SNR (2-8kHz)**	**Broadb. SNR**	**Rec. Rate**	**SNR (2-8kHz)**	**Broadb. SNR**	**Rec. Rate**
-6.5	-22.4	1.00	3.1	-12.9	1.00	6.4	-7.1	1.00
-7.5	-23.4	1.00	2.1	-13.9	0.99	5.4	-8.1	1.00
-8.5	-24.4	0.99	2.1	-13.9	1.00	4.4	-9.1	1.00
-9.5	-25.4	0.99	1.1	-14.9	0.99	4.4	-9.1	0.98
-10.5	-26.4	0.98	1.1	-14.9	1.00	4.4	-9.1	1.00
-10.5	-26.4	0.98	0.1	-15.9	0.96	3.4	-10.1	0.98
-10.5	-26.4	0.95	0.1	-15.9	0.99	2.4	-11.1	0.98
-11.5	-27.4	0.88	-0.9	-16.9	0.95	2.4	-11.1	1.00
-12.5	-28.4	0.61	-0.9	-16.9	0.97	1.4	-12.1	0.99
-12.5	-28.4	0.80	-1.9	-17.9	0.99	0.4	-13.1	0.97
-13.5	-29.4	0.05	-1.9	-17.9	0.97	0.4	-13.1	0.98
-13.5	-29.4	0.18	-2.9	-18.9	0.98	-1.6	-15.1	0.96
-13.5	-29.4	0.31	-4.9	-20.9	0.95	-3.6	-17.1	0.90
-14.5	-30.4	0.13	-6.9	-22.9	0.87	-5.6	-19.1	0.79
-14.5	-30.4	0.27	-8.9	-24.9	0.71	-7.6	-21.1	0.70
-16.5	-32.4	0.00	-10.9	-26.9	0.37	-9.6	-23.1	0.51
-16.5	-32.4	0.00	-12.9	-28.9	0.11	-11.6	-25.1	0.35
			-14.9	-30.9	0.01			
Ultrasonic (2017) protocol								
SNR (16kHz)	**Broadb SNR**	**Rec. Rate**	**SNR (16kHz)**	**Broadband SNR**	**Rec. Rate**	**SNR (16kHz)**	**Broadb SNR**	**Rec. Rate**
-10.80	-47.1	1.00	-2.9	-36.2	1.00	-10.5	-44.7	1.00
-11.80	-48.1	1.00	-3.9	-37.2	1.00	-10.5	-44.7	1.00
-11.80	-48.1	1.00	-4.9	-38.2	0.98	-11.5	-45.7	0.98
-12.30	-48.6	1.00	-4.9	-38.2	1.00	-12.5	-46.7	0.99
-12.80	-49.1	0.98	-5.9	-39.2	1.00	-12.5	-46.7	0.98
-12.80	-49.1	0.99	-6.9	-40.2	0.99	-13.5	-47.7	0.99
-13.30	-49.6	0.94	-6.9	-40.2	0.98	-14.5	-48.7	0.94
-13.80	-50.1	0.95	-7.9	-41.2	0.96	-14.5	-48.7	0.99
-13.80	-50.1	0.87	-7.9	-41.2	0.98	-15.5	-49.7	0.96
-14.80	-51.1	0.66	-8.9	-42.2	0.94	-16.5	-50.7	0.95
-14.80	-51.1	0.48	-9.9	-43.2	0.95	-16.5	-50.7	0.98
-15.80	-52.1	0.26	-10.9	-44.2	0.90	-18.5	-52.7	0.85
-16.80	-53.1	0.08	-12.9	-46.2	0.86	-20.5	-54.7	0.83
-17.80	-54.1	0.00	-14.9	-48.2	0.71	-22.5	-56.7	0.77
			-16.9	-50.2	0.53	-24.5	-58.7	0.77
			-18.9	-52.2	0.39			
			-20.9	-54.2	0.28			

Table 4: SNR (broadband and signal range) and receive rate of different interfering noises for Standard (2017) and Ultrasonic (2017) protocols

2.2.4 Signal and noise levels

Standard (2017) protocol						
Octave band centre frequency [Hz]	**Background noise [dB SPL]**	**Signal [dB SPL]**	**Traffic [dB SPL]**	**Music [dB SPL]**	**Signal (speech test only) [dB SPL]**	**Speech [dB SPL]**
16	59.5		55.6	53.5		50.2
31.5	54.3		60.5	55		44.3
63	35.4		79.4	77.2		54.1
125	36		79.2	77.1		70.5
250	20.5		78.3	78.4		76.7
500	19.1		76.1	74.5		78.6
1000	23.1		76	73.7		71.9
2000	21.9	51.1	72.7	68.5	55.2	69.2
4000	18.4	52.9	66.4	65.3	55.8	64.1
8000	17.2	50.9	62.5	65.5	53.5	65.3
16000	18.4		57.7	59.7		55.8
	SNR (2-8kHz) [dB]		-32.3	-16.5		-11.6
	SNR (broadband) [dB]		-15.5	-32.4		-25.1

Table 5: background noise, signal level and maximum interfering noise levels for Standard (2017) protocol chirp tests

Ultrasonic (2017) protocol					
Octave band centre frequency [Hz]	**Background noise [dB SPL]**	**Signal [dB SPL]**	**Traffic [dB SPL]**	**Music [dB SPL]**	**Speech [dB SPL]**
16	59.5		47.9	52.7	47.8
31.5	54.3		65.2	58.3	46.7
63	35.4		80.4	80.1	63.1
125	36		79.7	79	79.7
250	20.5		78.5	80.9	85.6
500	19.1		76.5	77	87.8
1000	23.1		76.2	74.4	80.7
2000	21.9		72.9	69.2	78.2
4000	18.4		66.6	66.9	73.4
8000	17.2		62.9	66.4	74.4
16000	18.4	39.9	57.7	60.8	64.4
	SNR (16kHz) [dB]		-17.8	-20.9	-24.5
	SNR (broadband) [dB]		-54.1	-54.2	-58.7

Table 6: background noise, signal noise and maximum interfering noise levels for Ultrasonic (2017) protocol chirp

tests

2.3 Reverberation time

The Ultrasonic (2017) protocol successful receive rate was 100% in all reverberation conditions – many tests for lower reverberation times were excluded for this protocol because of the ceiling effect; 1% error thresholds could not be obtained.

2.3.1 1% Error Threshold

The following table shows the estimated 1% error threshold from a 2nd order polynomial fit (fitted curves shown in the Appendix) of reverberation time and receive rate data (data from Maxwell lower hall, listening room and empty small reverberation chamber was excluded in the estimation). The thresholds for broadband RT and RT averaged over the signal frequency range are shown.

		1% Error Threshold [s]
Standard (2017) protocol	**Broadband RT (40-10kHz)**	2.85 $\pm$ 0.03
	Signal range RT (1.6-10kHz)	0.80 $\pm$ 0.04
Ultrasonic (2017) protocol	**Broadband RT (40-10kHz)**	**N/A** (receive rate 100% for all tests)
	Signal range RT (16kHz)	

Table 7: 1% error threshold reverberation time (ultrasonic protocol 100% receive rate for all tests – no threshold available)

2.3.2 Plot of RT vs receive rate

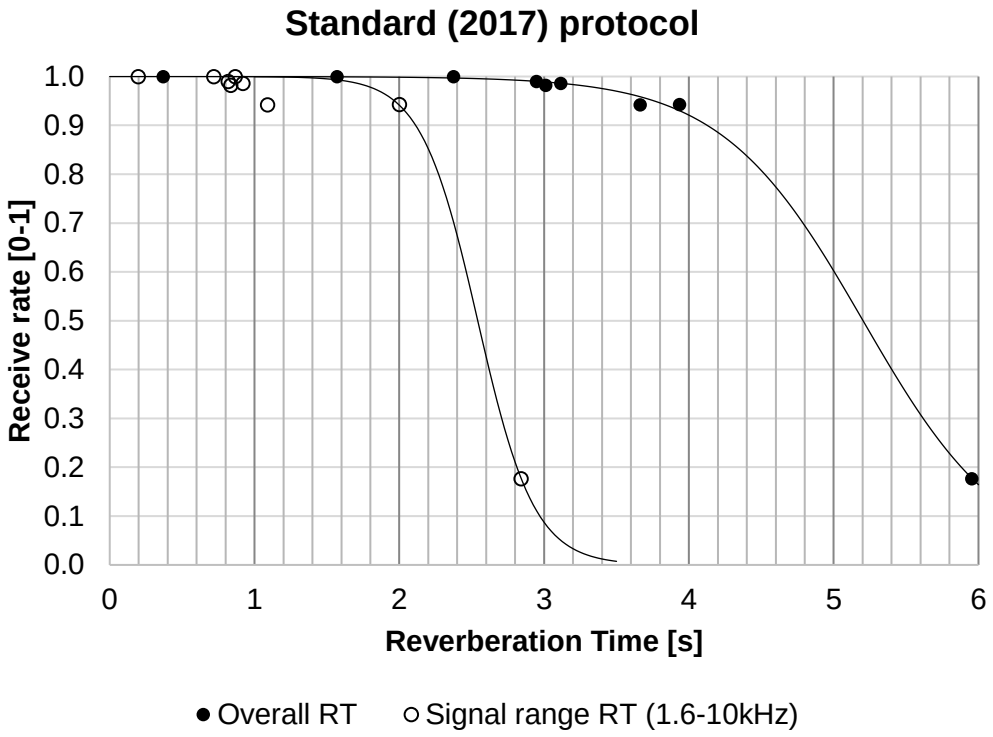

Figure 4: Reverberation time vs receive rate for Standard (2017) protocol chirps

2.3.3 Tabulated results

Room	RT (1.6-10kHz) [s]	RT (total) [s]	Standard (2017) protocol receive rate [0-1]	Ultrasonic (2017) protocol receive rate [0-1]
Large Rev. Chamber	2.00	3.94	0.943	1.000
Small Rev. Chamber (empty)	2.84	5.95	0.177	1.000
Small Rev. Chamber (absorption 1)	1.09	3.66	0.942	1.000*
Small Rev. Chamber (absorption 2)	0.92	3.12	0.986	1.000*
Small Rev. Chamber (absorption 3)	0.84	3.01	0.982	1.000*
Small Rev. Chamber (absorption 4)	0.82	2.95	0.990	1.000*
Small Rev. Chamber (absorption 5)	0.72	2.37	1.000	1.000*
Listening room	0.20	0.37	1.000	1.000
Maxwell Lower Hall	0.87	1.57	1.000	1.000

** Not tested, since receive rate was 1.000 for worst reverberation condition*

Table 8: Reverberation time and receive rate for both protocols

2.3.4 Room reverberation times

1/3 Oct. Band Ctr. Freq. [Hz]	Large Rev. Ch.	Small Rev. Chamber						List. room	Maxw. L. Hall
		Empty	Abs. 1	Abs. 2	Abs. 3	Abs. 4	Abs. 5		
	Reverberation time [ms]								
40	11066	8538	7980	7705	7557	7425	6954	1588	N/A
50	9065	11974	8955	7112	7939	8118	8122	979	1373*
63	6798	10193	8777	8053	7772	7623	6408	694	2473*
80	6460	7230	7072	7035	7254	6962	6427	476	2529*
100	4901	9082	8012	7582	7402	7206	5176	437	1864*
125	4754	10117	7813	6494	6477	6527	4535	358	1643
160	4726	6309	5764	3918	3362	3229	2804	362	2119*
200	3495	6718	4875	3884	3333	3185	2058	323	2363
250	3824	7642	3562	3474	2993	2737	2084	348	1959
315	3724	7353	3916	3185	2894	2754	1456	352	2013
400	3569	6998	3699	2596	2211	2276	1338	302	2045
500	3553	6239	2962	2361	2226	1951	1268	267	2066
630	3852	6485	2447	1891	2078	2140	1212	277	2047
800	3721	6682	2349	1641	1643	1583	1061	265	1947
1000	3538	6150	1862	1466	1427	1328	961	216	1836
1250	3340	5572	1752	1234	1174	1290	1034	217	1579
1600	3165	5318	1496	1297	1081	1077	897	253	1320
2000	3017	4510	1405	988	1031	1024	948	191	1231
2500	2738	3769	1327	1093	936	915	852	179	1068
3150	2468	3395	1228	1041	963	941	791	199	1071
4000	2027	2748	1135	977	826	829	688	187	912
5000	1617	2083	1031	872	806	784	684	195	778
6300	1258	1673	868	798	763	730	650	186	596
8000	979	1261	740	661	617	592	525	191	485
10000	732	818	584	551	493	479	439	186	351
Total A	3286	6332	3506	2771	2544	2488	1517	255	1687
Average	3935	5954	3664	3116	3010	2948	2375	369	1570
Average 1.6-10kHz	2000	2842	1090	920	835	819	719	196	868

Table 9: Reverberation time of tested rooms (Early Decay Time)*

2.3.5 Background and signal noise levels

	Large Rev. Chamber			Small Rev. Chamber		
Octave band centre freq. [Hz]	**Backg. noise [dB SPL]**	**Standard (2017) protocol [dB SPL]**	**Ultrasonic (2017) protocol [dB SPL]**	**Backg. noise [dB SPL]**	**Standard (2017) protocol [dB SPL]**	**Ultrasonic (2017) protocol [dB SPL]**
16	35.1			45.20		
31.5	31.4			44.40		
63	29.7			38.50		
125	19.7			32.90		
250	16.9			31.90		
500	18.9			30.50		
1000	21.8			30.80		
2000	20.6	76.4		31.40	91.90	
4000	17.5	75.3		30.90	90.60	
8000	17.0	71.5		31.20	87.30	
16000	18.3		72.4	34.10		83.20

Table 10: Background and signal noise levels

Appendix

Sigmoid curve fit details

The sigmoid curves in Figures 2, 3 and 4 were obtained by fitting the function f to the measured receive rate data:

$$f(x) = (e^{ax+b} + 1)^{-1} \quad (1)$$

where x is the signal-to-noise ratio or reverberation time, and a and b are parameters which are chosen to minimise differences between the function and the measured data. The values of parameters a and b for both protocols and interference conditions are given in the tables below, and provide an estimate of receive rate under different conditions for each protocol.

		a, b (in chirp freq. range)	**a, b (broadband)**
Standard (2017) protocol	**Traffic-shaped noise**	-1.799, -23.131	-1.798, -51.656
	Music	-0.678, -6.823	-0.678, -17.642
	Speech	-0.352, -3.446	-0.352, -8.211
Ultrasonic (2017) protocol	**Traffic-shaped noise**	-1.607, -24.183	-1.607, -82.609
	Music	-0.342, -6.024	-0.342, -17.400
	Speech	-0.219, -6.337	-0.219, -13.820

Table 11: Best-fit values of parameters a and b of sigmoid function (Equation 1) for both protocols under different noise interference conditions

		a, b (in chirp freq. range)	**a, b (broadband)**
Standard (2017) protocol	**Reverberation time**	5.123, -13.020	2.041, -10.618

Table 12: Best-fit values of parameters a and b of sigmoid function (Equation 3.1) for standard protocol with reverberation interference

Graphs of polynomial curve fitting

The following graphs show the 2nd degree polynomial curves and data points used to determine the 99% receive rate for both protocols under reverberation and noise interference conditions.

Reverberation time interference

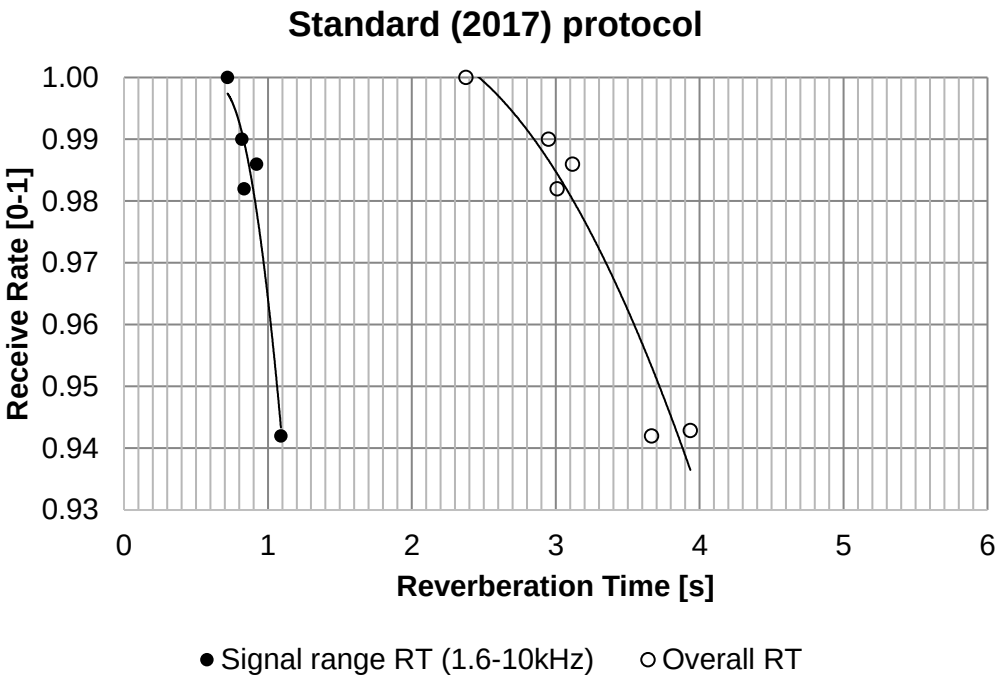

Figure 5: Broadband and signal band reverberation time vs receive rate of Standard (2017) protocol chirps; showing 2nd order polynomial fit

Noise interference

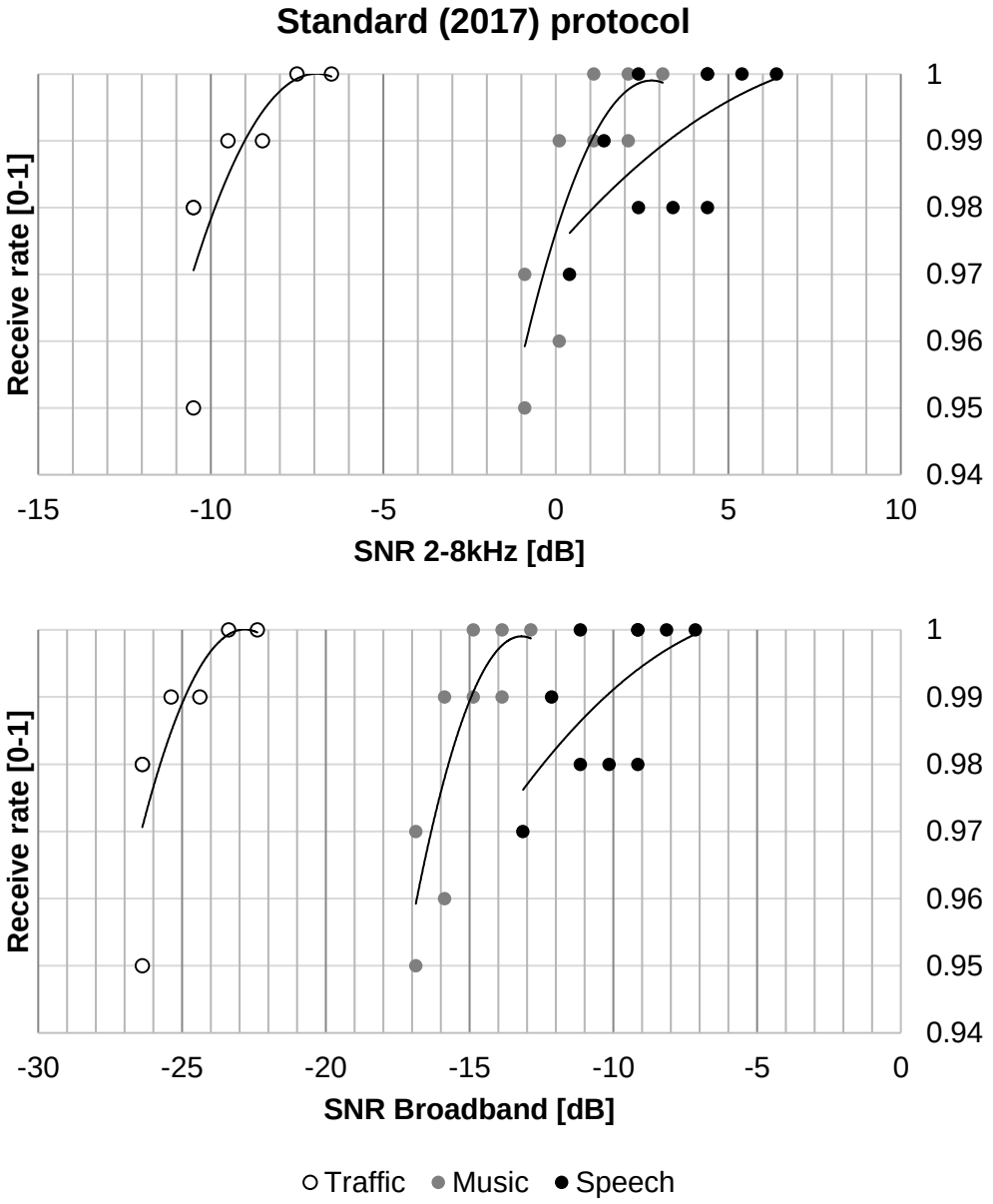

Figure 6: Interfering noise SNR (broadband and signal band) vs receive rate of Standard (2017) protocol chirps; showing 2nd order polynomial fit

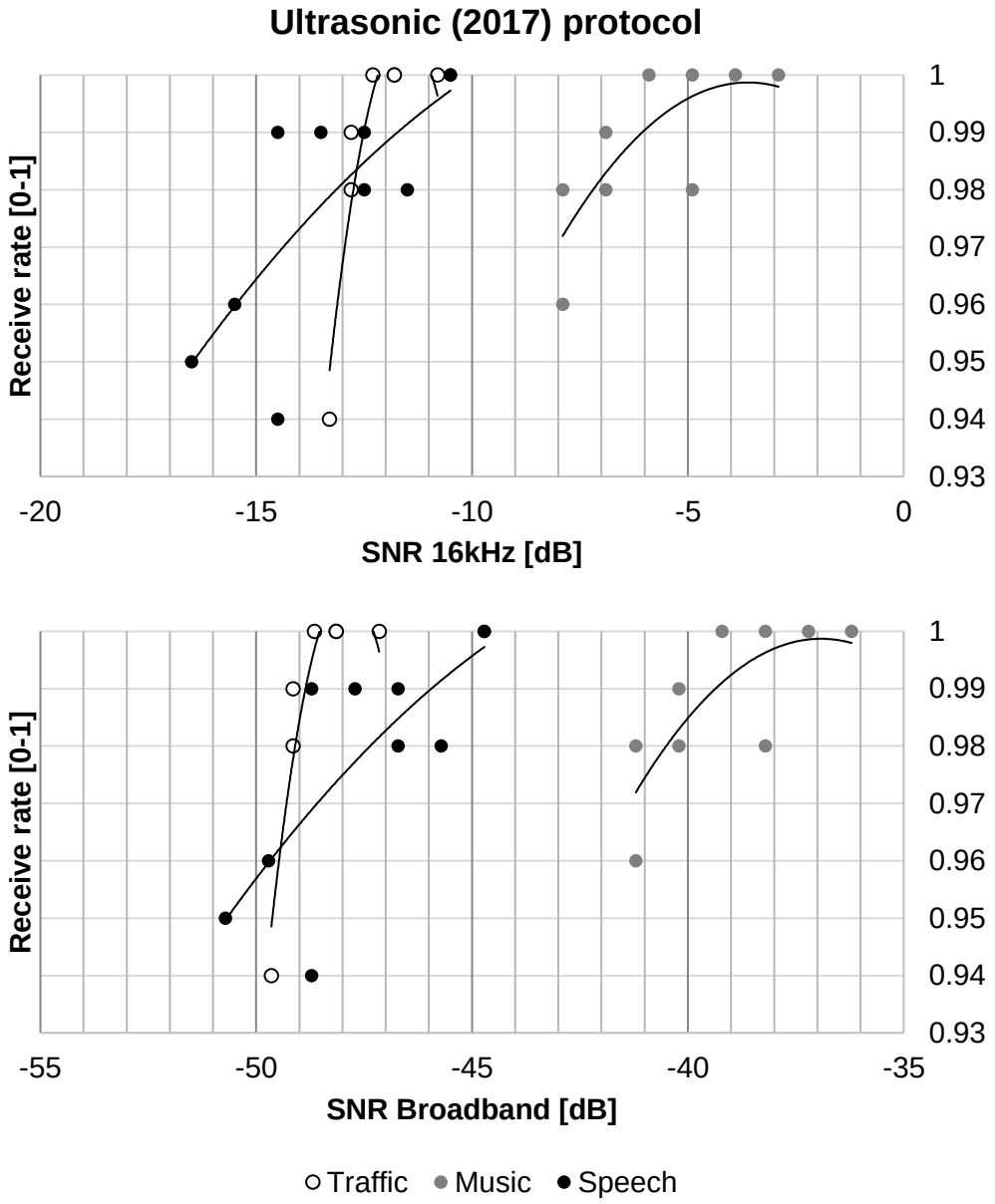

Figure 7: Interfering noise SNR (broadband and signal band) vs receive rate of Ultrasonic (2017) protocol chirps; showing 2nd order polynomial fit