Sound Effects

Exploring acoustic cyber-weapons

Matt Wixey

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All references cited are at the end of the slide deck, available on the DEF CON media server!

Matt Wixey

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- PhD student at UCL
- Previously worked in LEA doing technical R&D
- Black Hat USA, DEF CON, ISF Congress, BruCon, 44Con, BSides, etc

Disclaimer

- Undertaken as part of my PhD research at UCL
- Supervisors & co-authors:
  - Prof. Shane Johnson (https://www.ucl.ac.uk/jill-dando-institute/about-us/people/academic-staff/shane-johnson)
  - Assoc. Prof. Emiliano De Cristofaro (https://emilianodc.com/)
- The following is presented for educational purposes only

Why this talk?

- DEF CON 25: “See no evil, hear no evil”
  – https://www.youtube.com/watch?v=gFTiD7EnVjU
- Interested in unconventional uses of sound, applied to security

Why should you care?

- Novel class of attack
- Empirical experimentation
- Increasing attack surface
- Building on previous work on:
  - Malware and physical harm
  - Acoustic harm
  - Digital/physical crossover attacks

Background

Malware and physical harm – some examples

Background

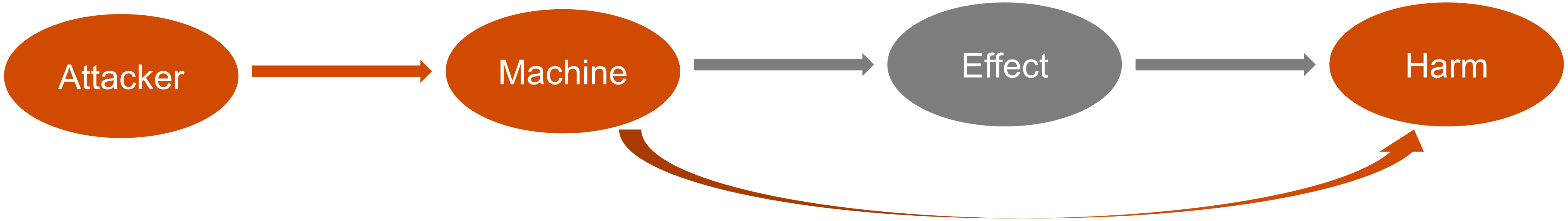
- Digital/physical malware: Stuxnet, Mirai, Mirksy et al, 2019
- Malware inadvertently affecting physical kit: Conficker, Wannacry
- Medical implant vulnerabilities
  - Halperin et al, 2008; Rushanan et al, 2014; Williams & Woodward, 2015; Rios & Butts 2019
- Vehicle vulnerabilities (Othmane et al, 2013; Valasek & Miller 2015)

Malware and harm - effects

Background

- Typically, there's an indirect relationship

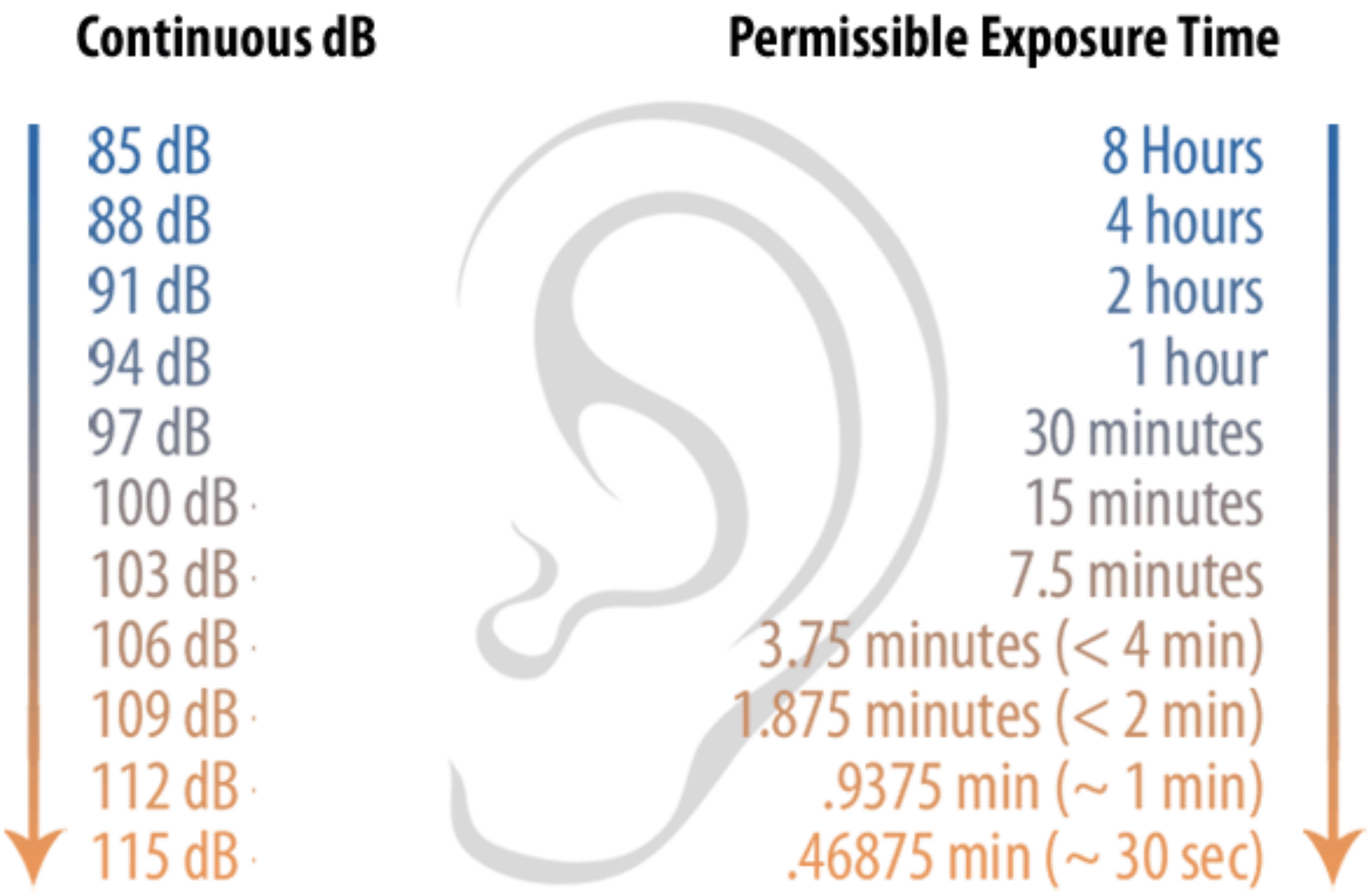
- What about malware that *directly* affects humans?



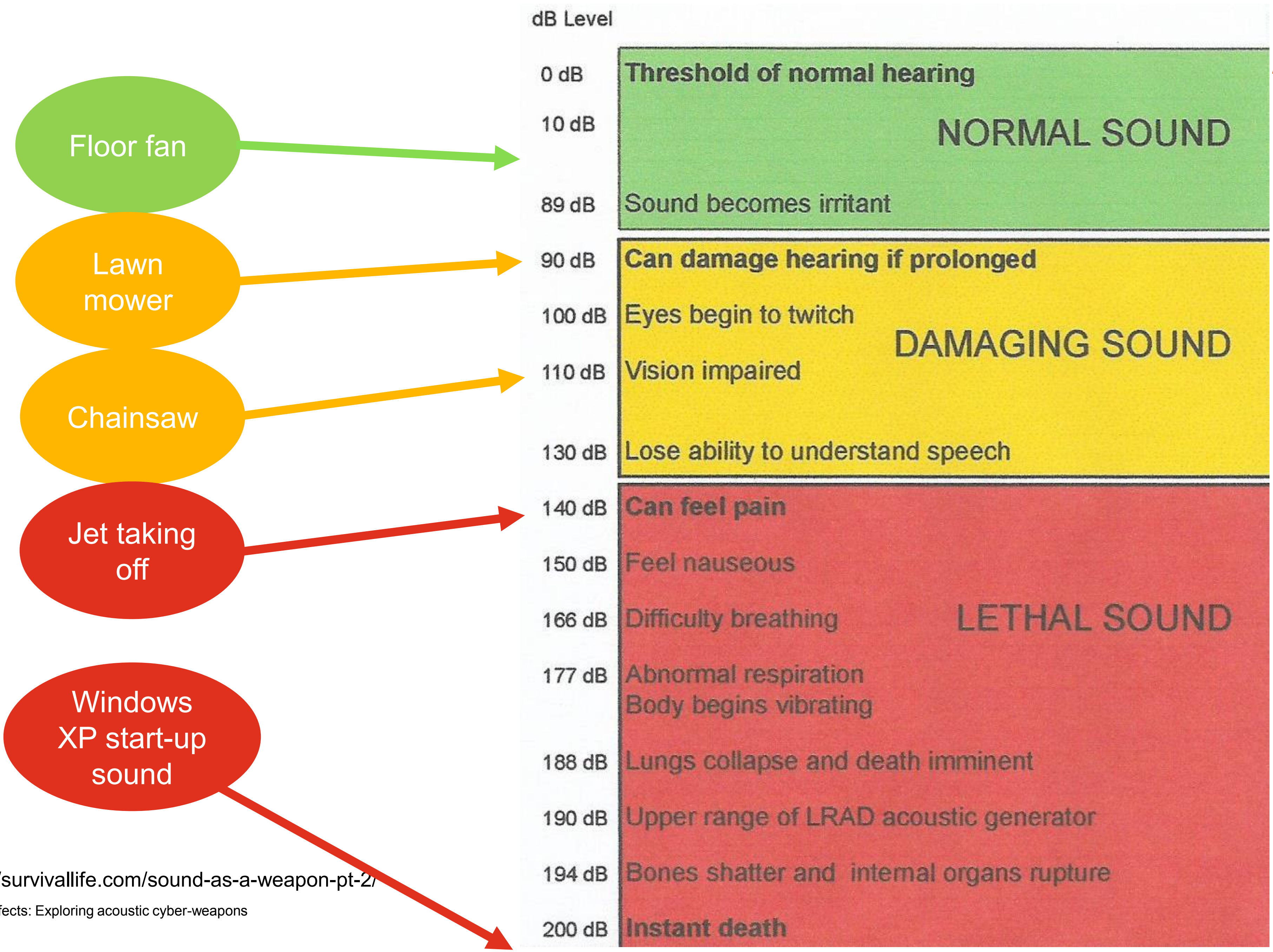
– Poulsen, 2008; Oluwafemi et al, 2013; Ronen & Shamir, 2016; Rios & Butts, 2017

Sound as a weapon

Background



http://dangerousdecibels.org/education/information-center/decibel-exposure-time-guidelines/



https://survivallife.com/sound-as-a-weapon-pt-2/

Acoustics and harm

What can we hear?

- Ultrasound & infrasound: above/below human hearing threshold
- Traditionally 20Hz – 20kHz (Durrant & Lovrinic, 1995)
  - This is a misconception: thresholds vary widely
  - This talk:
    - High-frequency noise (HFN): 17 - 21kHz
    - Low-frequency noise (LFN): 60 - 100Hz

Imperceptibility

- Basing a definition on a lack of a property is problematic
  - Duck & Leighton, 2018
- Perceptibility not a case of arbitrary cut-off points
- Mechanisms not fully understood (Koch, 2017)
- Significant variation in thresholds
  - Leighton, 2018; Leventhall et al, 2003; van Wieringen & Glorieux, 2018

Imperceptibility

- Depends on volume, background noise, previous exposure, etc
- Sound may be perceived as vibration (Leventhall et al, 2003)
  – Or audible ‘subharmonics’ (Ashihara et al, 2006; Howard et al, 2005)
- Likelihood declines non-linearly (Muhlhans, 2017)
- For HFN, threshold increases with age
  – Macca et al, 2015; van Wierengen & Glorieux, 2018

Adverse physiological effects - HFN

Acoustics and harm

- Susceptibility differs (Leighton, 2016; Qibai & Shi, 2004)
- No reports of high frequencies causing hearing loss, but:
  - Adverse effects on hearing (Duck & Leighton, 2018)
  - Temporary threshold shifts (Acton and Carson, 1967)
  - Reduction in hearing sensitivity in audible range (Chopra et al, 2016; Grzesik & Pluta, 1986; Macca et al, 2015; Wilson et al, 2002)
  - Neurasthenia, cardiac neurosis, hypotension, bradycardia, functional changes in CV and CNS (Smagowska & Pawlaczyk-Łuszczy´nska, 2013)

Adverse psychological effects - HFN

- Nausea, fatigue, headaches
  – Duck & Leighton, 2018; Howard et al, 2005; Von Gierke & Nixon, 1992
- Tinnitus and ear pain (Chopra et al, 2016; Fletcher et al, 2018a)
- Irritation (Ueda et al, 2014)
- Somnolence, dizziness, palpitations, decreased concentration (Smagowska & Pawlaczyk-Łuszczy´nska, 2013)

Adverse physiological effects - LFN

- Temporary threshold shifts (Leventhall et al, 2003)
- Some correlation with:
  - Heart ailments, chronic insomnia (Mirowska & Mroz, 2000)
  - Elevated cortisol levels (Bengtsson, 2003)

Adverse psychological effects - LFN

- Annoyance (Pawlaczyk-łuszczy´nska et al, 2005; Persson & Rylander, 1988; Storm, 2009) most common, but also:
  - Headaches and palpitations (Møller & Lydolf, 2002)
  - Deterioration in performance & productivity (Bengtsson, 2003; Benignus et al, 1975; Kaczmarska & Łuczak, 2007)
  - Lower levels of cooperation & agreeableness (Waye et al, 1997)
  - Depressive symptoms & distress (Stansfeld & Shipley, 2015)
  - Even at very moderate levels:
    - 40-45dBA (Bengtsson, 2003; Persson & Bjorkman, 1988; Waye et al, 1997)

Caveats

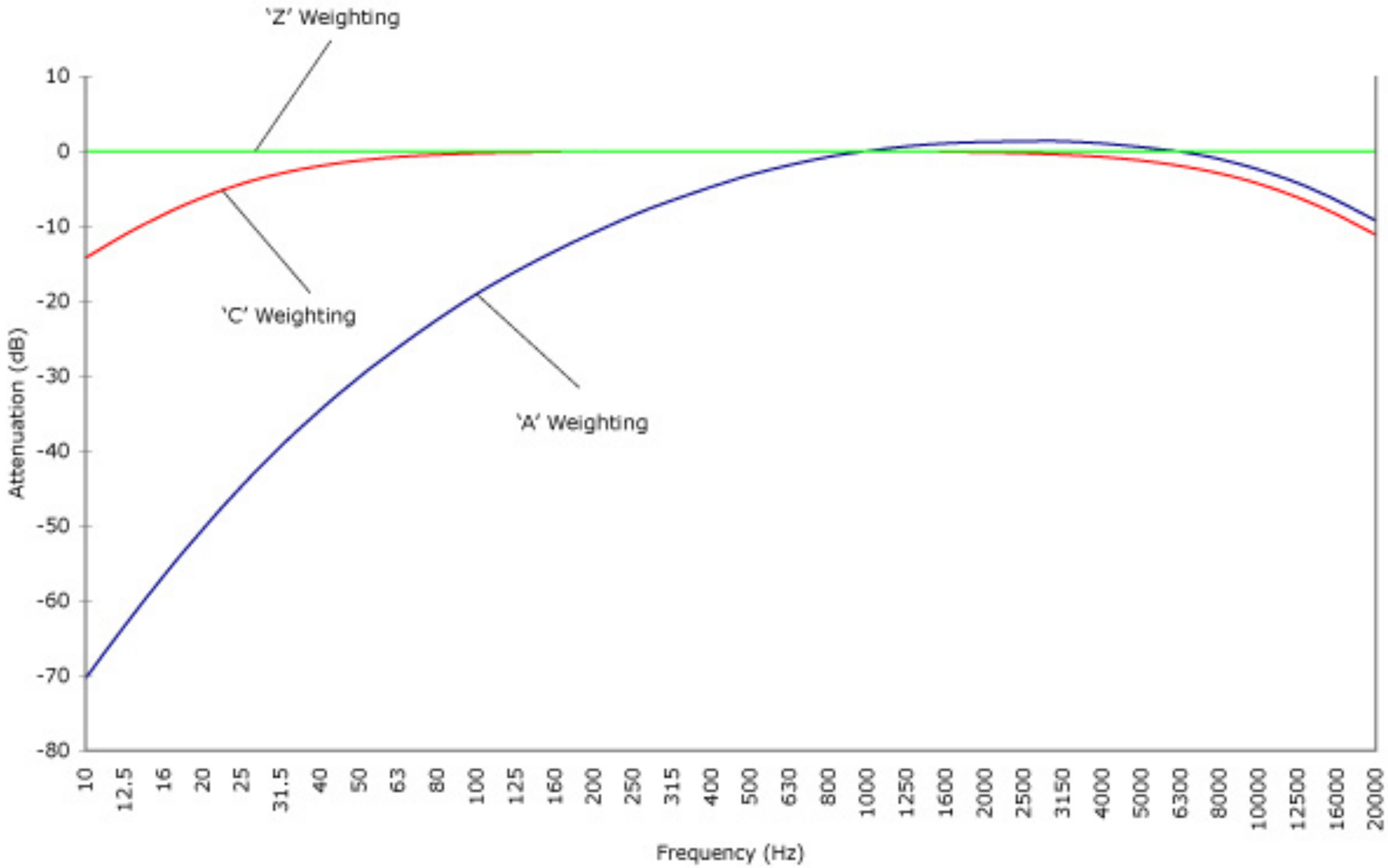
- Data often sparse and anecdotal (Leighton, 2018)
- Easily misinterpreted (Duck & Leighton, 2018)
- Detailed knowledge of "noise dose" not always present
  - Andringa & Lanser, 2013; Donder et al, 2018
- Many effects not reproducible in labs (Fletcher et al, 2018b)
  - Ethical restrictions (Fletcher et al 2018a, 2018b; Leighton, 2018)
  - Possible "nocebo" effect
- But significant base for adverse effects in subset of population

Exposure guidelines - HFN

- Significant differences in methodology and implementation
- Mostly in occupational context
- Often based on small samples
- Samples often made up of mostly adult males (Leighton, 2018)

	8kHz	10kHz	12.5kHz	16kHz	20kHz	25kHz	31.5kHz	40kHz	50kHz
Parrack 1966	-	-	-	-	140	140	140	140	140
Grigor'eva 1966	80	85	90	90	120	120	120	120	120
Acton 1968	75	75	75	75	110	110	110	-	-
Parrack 1969	-	80	80	80	105	110	115	115	115
Japan 1971	90	90	90	90	110	110	110	110	110
USSR 1975	-	-	75	85	110	110	110	110	110
Acton 1975-6	75	75	75	75	75	110	110	110	-
USAF 1976	-	-	85	85	85	85	85	85	-
ILO 1977	-	-	75	85	110	110	110	110	110
Sweden 1978	-	-	-	-	105	110	115	115	115
Norway 1978	-	-	-	-	x	120	120	120	120
ACGIH 1979	-	80	80	80	105	110	115	115	115
Canada 1980	80	80	80	80	80	110	110	110	110
Australia 1981	-	75	75	75	75	110	110	110	110
USSR 1983	-	-	80	90	100	105	110	110	110
INIRC-IRPA 1984	-	-	-	-	75	110	110	110	110
INIRC-IRPA 1984	-	-	-	-	70	100	100	100	100
Health Canada 1991	-	-	-	75	75	110	110	110	110
Poland 2002	-	80	80	80	90	105	110	110	-
Poland 2002	-	100	100	100	110	125	130	130	-
ACGIH 2004	-	-	88	89	92	94	-	-	-
ACGIH 2004	-	105	105	105	105	140	145	145	145
US DoD 2010	-	80	80	80	105	110	115	115	115
EARS Project 2015	-	75	75	75	77	102	110	110	110

Weighting



https://www.cirrusresearch.co.uk/blog/2011/08/what-are-a-c-z-frequency-weightings/

Exposure guidelines - HFN

- Consensus that A-weighting is inappropriate
- Underestimates higher frequencies (Lawton, 2001; Leighton, 2018)
- SPL re 20 µPa is commonly used
- As is Z-weighting (flat frequency response from 10Hz – 20kHz, no attenuation for sounds above/below ‘audible range’)

Exposure guidelines - LFN

- Fewer guidelines exist
- Perhaps because primary effects are subjective, at moderate levels?
- Again, methodology differs significantly

Exposure guidelines - LFN

- Reference curve proposed by Defra (Moorhouse et al, 2011)
- Devised after assessment of previously published curves
- G-weighting (ISO 7196:1995) commonly used for 1Hz - 20Hz
  - But not LFN (Koch, 2017)

Exposure guidelines - LFN

10Hz	12.5Hz	16Hz	20Hz	25Hz	31.5Hz	40Hz	50Hz	63Hz	80Hz	100Hz	125Hz	160Hz
92	87	83	74	64	56	49	43	42	40	38	36	34

Previous work

Sound in security research

Previous work

- Covert communications channels (HFN)
  - Mobile devices (Deshotels, 2014)
  - Covert mesh networks (Hanspach & Goetz, 2014)
  - Dreadphone/Spectregram (Wixey, 2017)
  - Many consumer devices capable of emitting HFN (Filonenko et al, 2010)

Sound in security research

Previous work

- Disruption of echolocation systems for obstacle avoidance
  - Ultrasonic altimeters on drones (Wixey, 2017)
  - Tesla vehicles (Yan et al, 2016)
- Corruption of data written to hard disk drives
  - Blue Note (Bolton et al, 2018)
- Ultrasonic tracking beacons for targeted marketing
  - Filonenko et al, 2010; Cunche & Cardoso, 2018

Acoustic weapons – FAQs

Previous work

- Brown Note
- Paranormal experiences (Tandy, 2000; Parsons et al, 2008)
- US Embassy in Cuba (Leighton, 2018)

Acoustic weapons

Previous work

- Many misunderstandings (Muhlhans, 2017; Vinokur, 2004)
- Significant practical issues (Altmann, 2001)
  - Threshold shifts probably not of interest to attackers
  - Challenging to cause targeted, directional effects
  - LFN: high propagation, low directionality, size restrictions
  - HFN: low propagation, size restrictions
- Need close proximity, rapid diffusion (Bartholomew & Perez, 2018)

Our experiment

Hypothesis

Our experiment

- HFN and LFN may be imperceptible to subset of population
- And, above certain levels, may cause adverse effects
- Some consumer equipment can emit HFN and LFN
- Could an attacker develop malware or attacks to:
  - Cause a device to emit HFN or LFN…
  - … at levels at or exceeding those in maximum permissible guidelines…
  - … and therefore cause adverse effects?

Experiment outline

- Develop attacks and malware
- Which can control volume and speaker output in consumer devices
- Play/stream tones at a set of high and low frequencies
- Measure output with a sound level meter
- Compare output to maximum permissible levels

Ethics

- No human subjects involved in experiment
- Ethics exemption granted by UCL Ethics Committee
- Full risk assessment conducted prior to experimentation
- Relevant safety precautions (ear defenders, anechoic chamber)
- Brands/models/code not released, to minimise risk

Attack scenarios

Our experiment

- Attacker seeking to affect performance of employees/staff
- Attacker seeking to affect performance of organisation (at scale)
- Targeted harassment campaigns
- Low-grade cyber-weapons

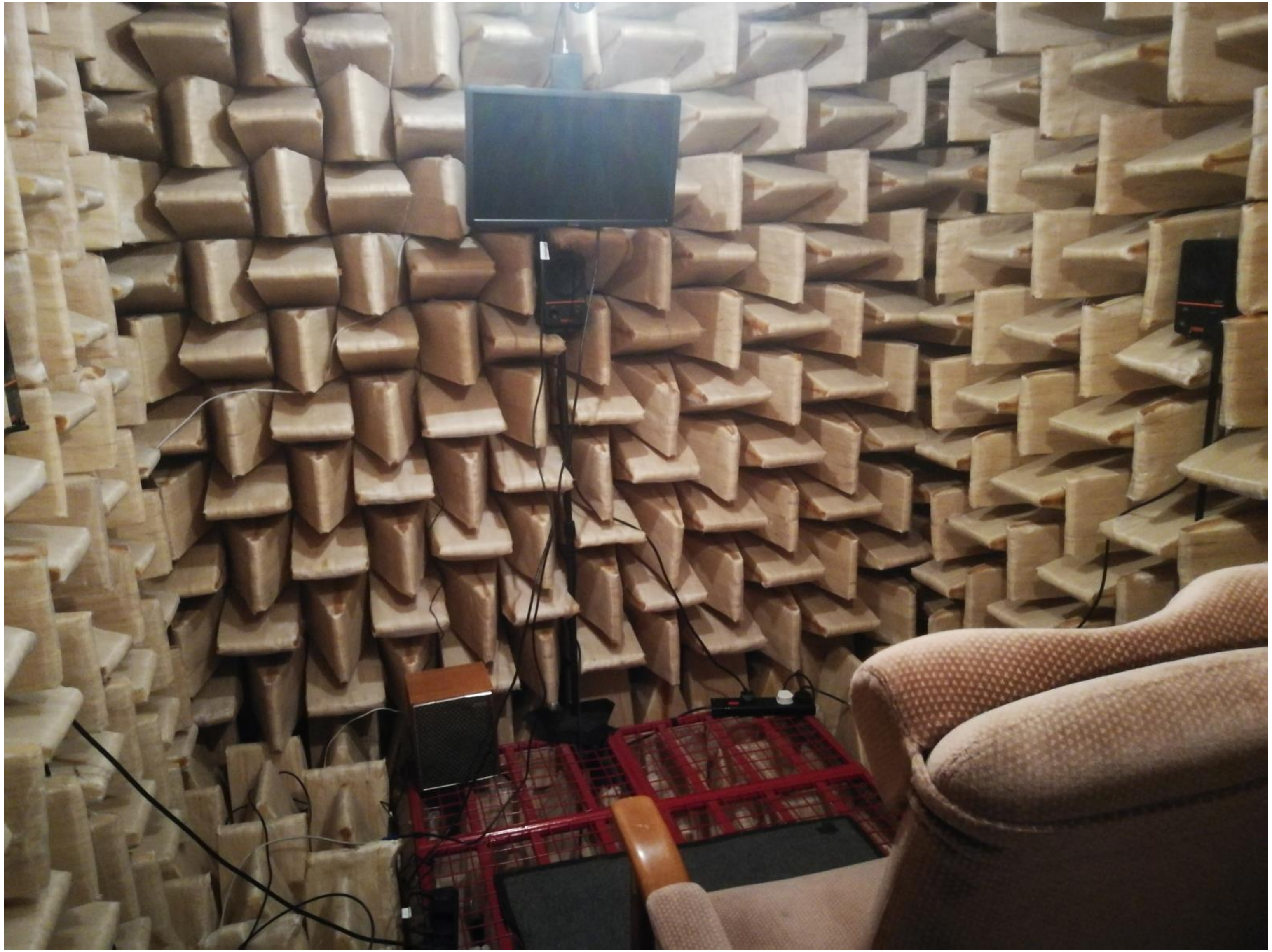
Attack scenarios

Our experiment

Device	Environment	Price	Attack Vector	Access Type
Laptop	Home, business	$1,000	Malware infection	Remote or local
Mobile phone	Home, business	$200	Malware infection	Remote or local
Bluetooth speaker	Home, business, public	$50	Bluetooth	Within range
Smart speaker	Home, business, public	$200	Vulnerability	Remote or local
Headphones	Home, business	$400	Multiple	Remote or local
Vehicle PA	Public	$35	USB	Local
Parametric speak.	Business, public	$250	Multiple	Local
Vibration speaker	Home, business, public	$70	Bluetooth	Within range

Test environment

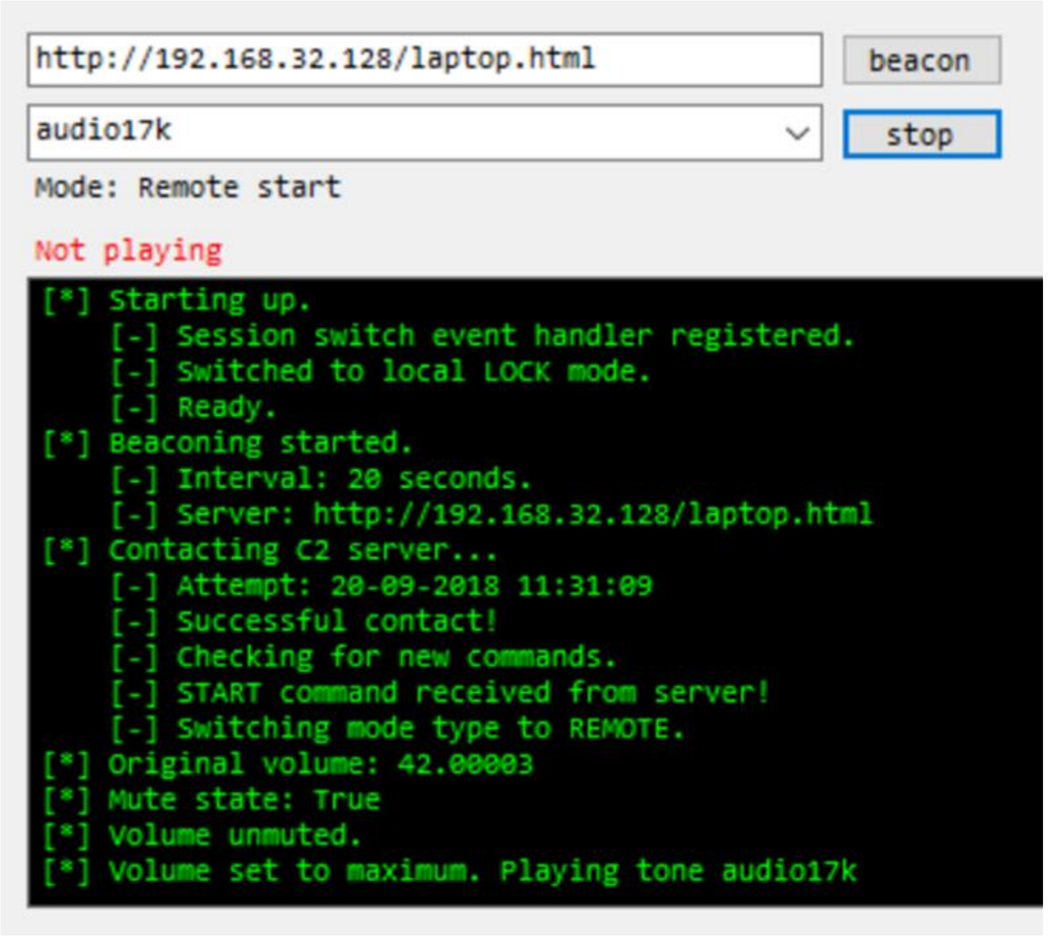
Our experiment



Windows PoC malware

Our experiment

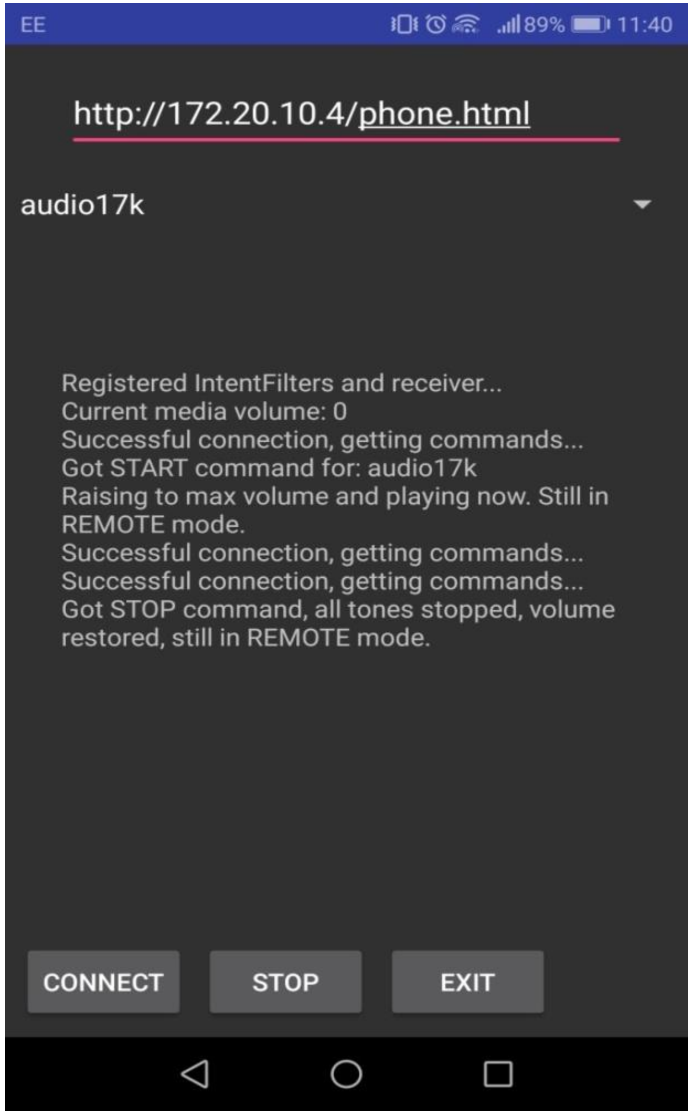
- Tones embedded
- Local mode (plays on lock)
- Remote mode (C2 channel)
- Volume increased to 100%
- Lowered to original level afterwards



PoC Android malware

Our experiment

- Local mode (plays on lock)
- Remote mode (C2 channel)
- Volume increased to 100% for attack
- Lowered to original level afterwards



Smart speaker

Our experiment

- Known vulnerability to control audio
- Attacker on local network, or do DNS rebinding attack
- Python script to scan for speakers
- If inactive, stream tone from attacker's web server at 100% volume
- Then restore volume to original state

Headphones

Our experiment

- Over-ear design
- Connected to laptop over Bluetooth
- Placed closer to SLM (1cm)

Vibration & Bluetooth speakers

Our experiment

- Vibration speakers
  - No diaphragm cone
  - Uses a coil on a movable plate which pushes against surface
  - Smaller profile, possibly attractive as localised acoustic weapons
- Paired over Bluetooth (same as Bluetooth speaker)

Parametric speakers

Our experiment

- Ultrasonic carrier waves
- High-intensity directional audio (Pompei, 2002)
- No smart capabilities
- Connected to laptop
- Low profile and cost, and directional properties
- Could be attractive as portable acoustic weapon

Vehicle-mounted PA system

Our experiment

- No network interfaces
- Autoplays audio from an inserted storage device (USB/SD)

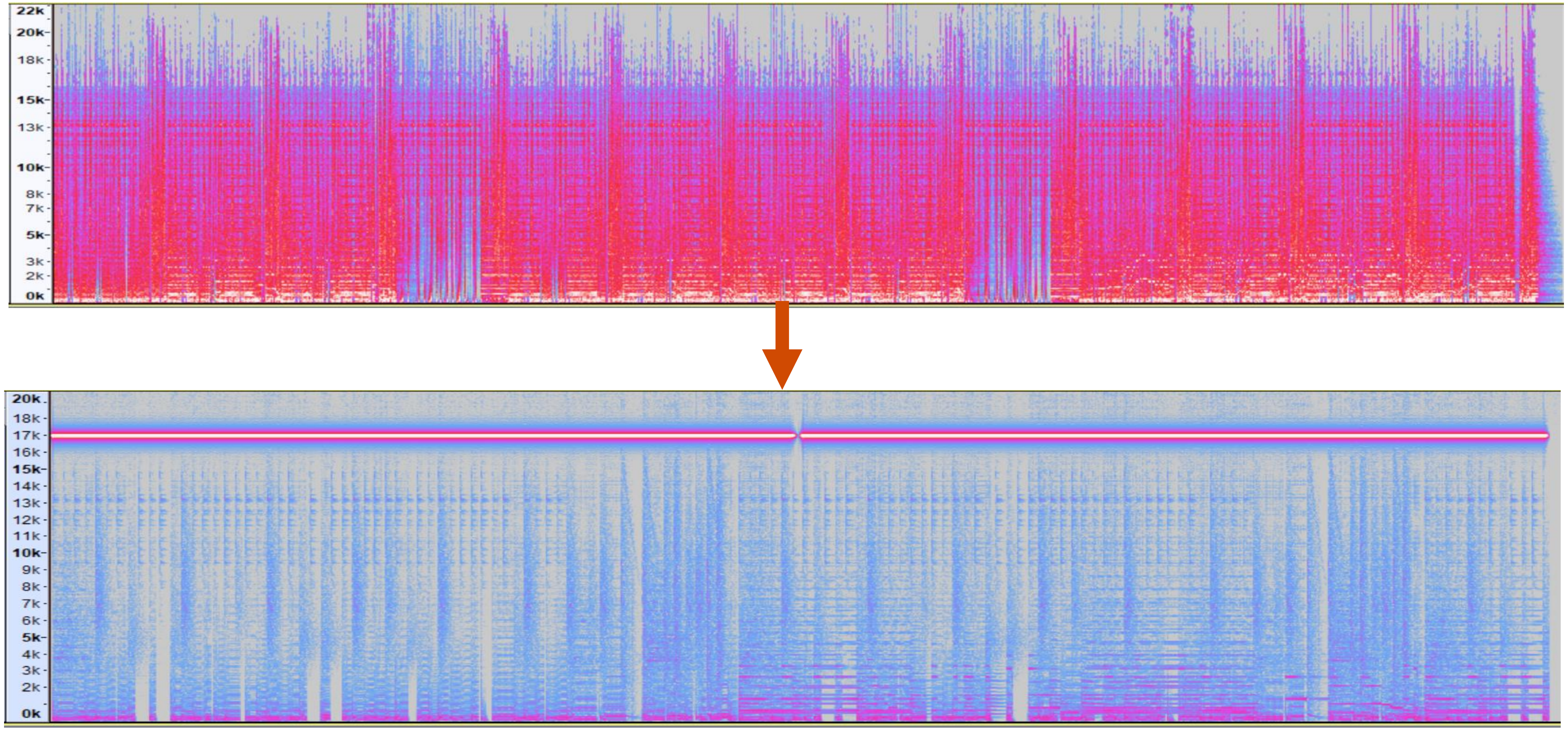
Additional attacks – HTML5

Our experiment

- HTML5 audio tag
- Autoplay on visit to site
- Now disabled in some browsers
- Depends on currently set system volume (can’t change client-side)

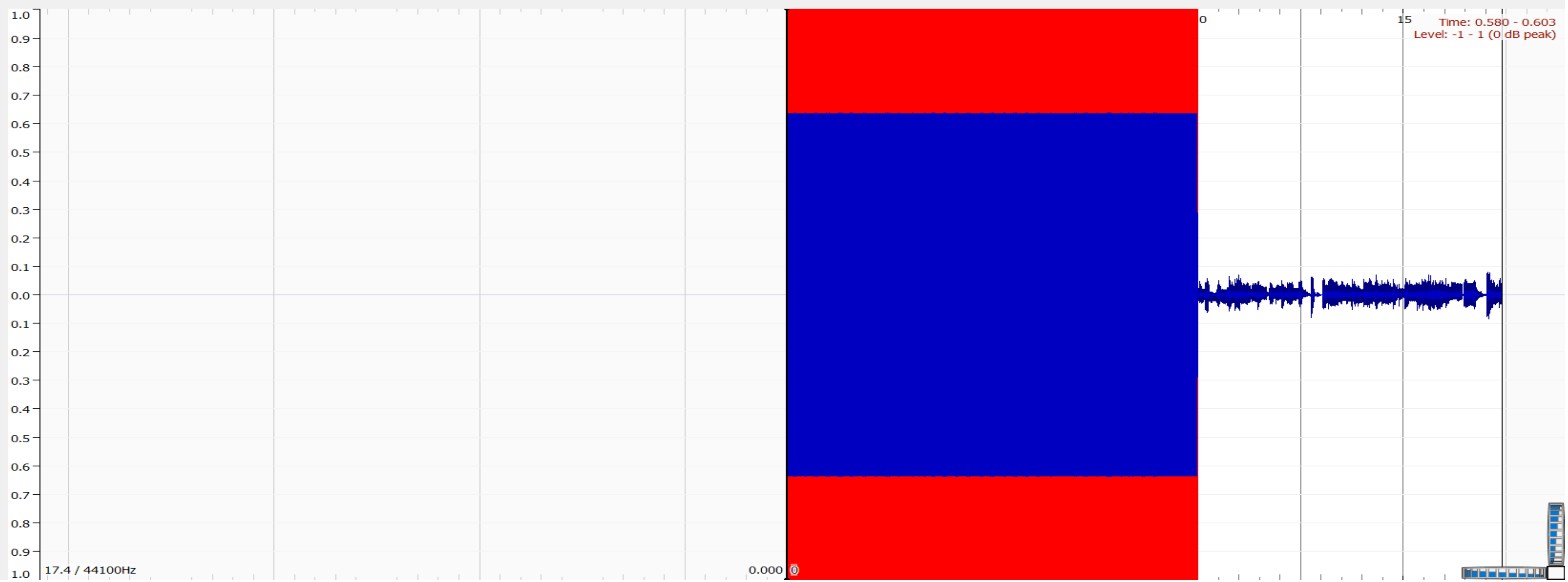
Additional attacks – manipulation of audio

Our experiment



Additional attacks - manipulation of audio

Our experiment



Measurement

Our experiment

- Class I sound level meters
- “Precision grade”: narrower tolerances, wider frequency range
- Spot-calibrated
- Very expensive
- But you can hire them and send them back via courier
  - That awesome time I almost lost ~£20,000

Measurement

Our experiment

- Each device placed in anechoic chamber with Class I SLM
- Via attacks, played a sine wave tone at 44.1kHz sample rate
- Single frequency (checked with spectrograms)
- Each tone on each device played for 10 minutes
- Surface temperature also measured before/after attack

Measurement

Our experiment

- Z-weighting used for 17kHz and 19kHz
- Proprietary high-pass filter weighting used for 21kHz
- Z-weighting used for LFN

Results - HFN

Our experiment

	17kHz	19kHz	21kHz(HPE)	40kHz
Laptop	63	64.5	45.5	-
Mobile phone	59.4	58.3	16.9	-
Bluetooth speaker	59.4	48.5	54.5	-
Smart speaker	**86**	35.2	43.8	-
Headphones	**87.5**	81.2	79.8	-
3 laptops	65.6	63.8	57.5	-
3 phones	59.8	61.1	45.3	-
Vehicle PA	75.3	20.5	18.5	-
Vibration speaker	47.7	36.1	27.3	-
Parametric speaker	**85.1**	84.2	**97.1**	**117.7**
Parametric (no music)	-	-	-	89.7
Parametric (music)	-	-	-	84.9

Results - LFN

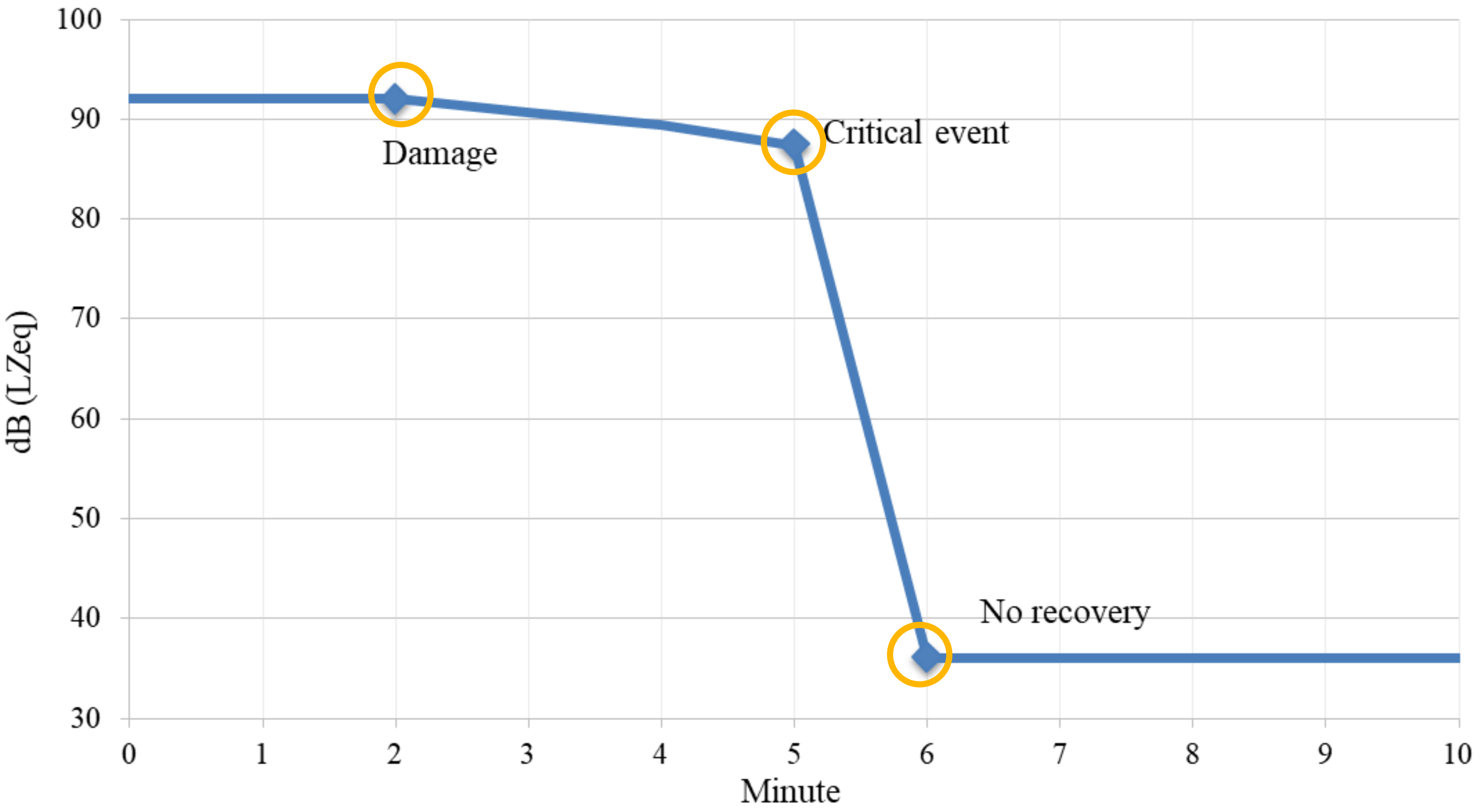
Our experiment

	60Hz	80Hz	100Hz
Laptop	2	0.1	3
Mobile phone	1	1.2	6.5
Bluetooth speaker	38.2	**51**	**64.2**
Smart speaker	**47.5**	**59**	**71.6**
Headphones	37.5	39.9	**40.2**
3 laptops	1.4	-0.3	4.7
3 phones	3.3	1.6	12.5
Vehicle PA	13.7	22.6	33.7
Vibration speaker	24	21.1	18.4
Parametric speaker	-0.6	0.5	28.6

Other results of interest

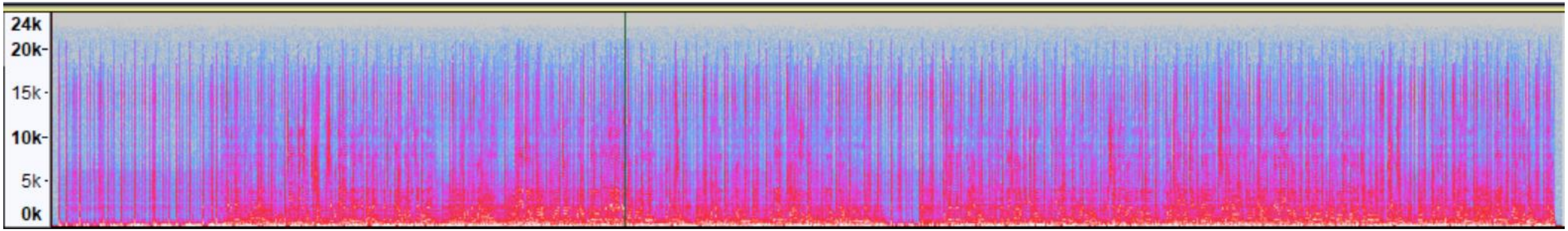
Our experiment

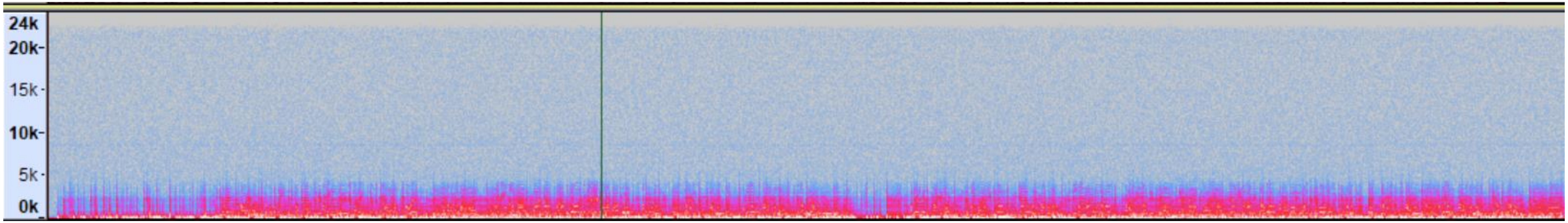
- Vibration speaker vibrated so much that it continuously fell over
- Burning smell from smart speaker
  – Further testing showed it was permanently damaged…


100
90
80
70
60
50
40
30
dB (LZeq)
Damage
Critical event
No recovery
0
1
2
3
4
5
6
7
8
9
10
Minute

Smart speaker damage

Our experiment



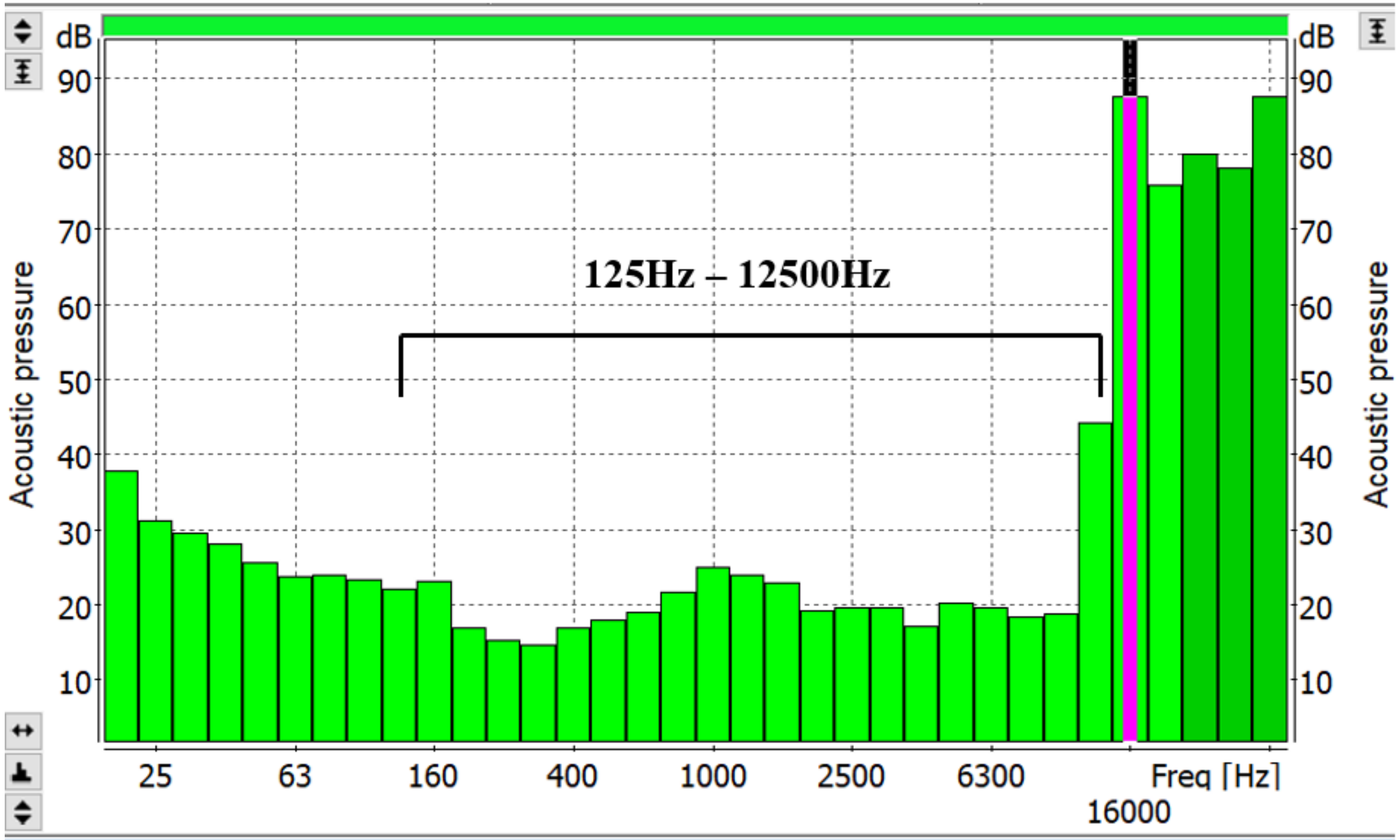


Disclosure

- Reported to manufacturers, who were responsive and cooperative
- Informed updates had been rolled out to address the issue

Audible components - headphones

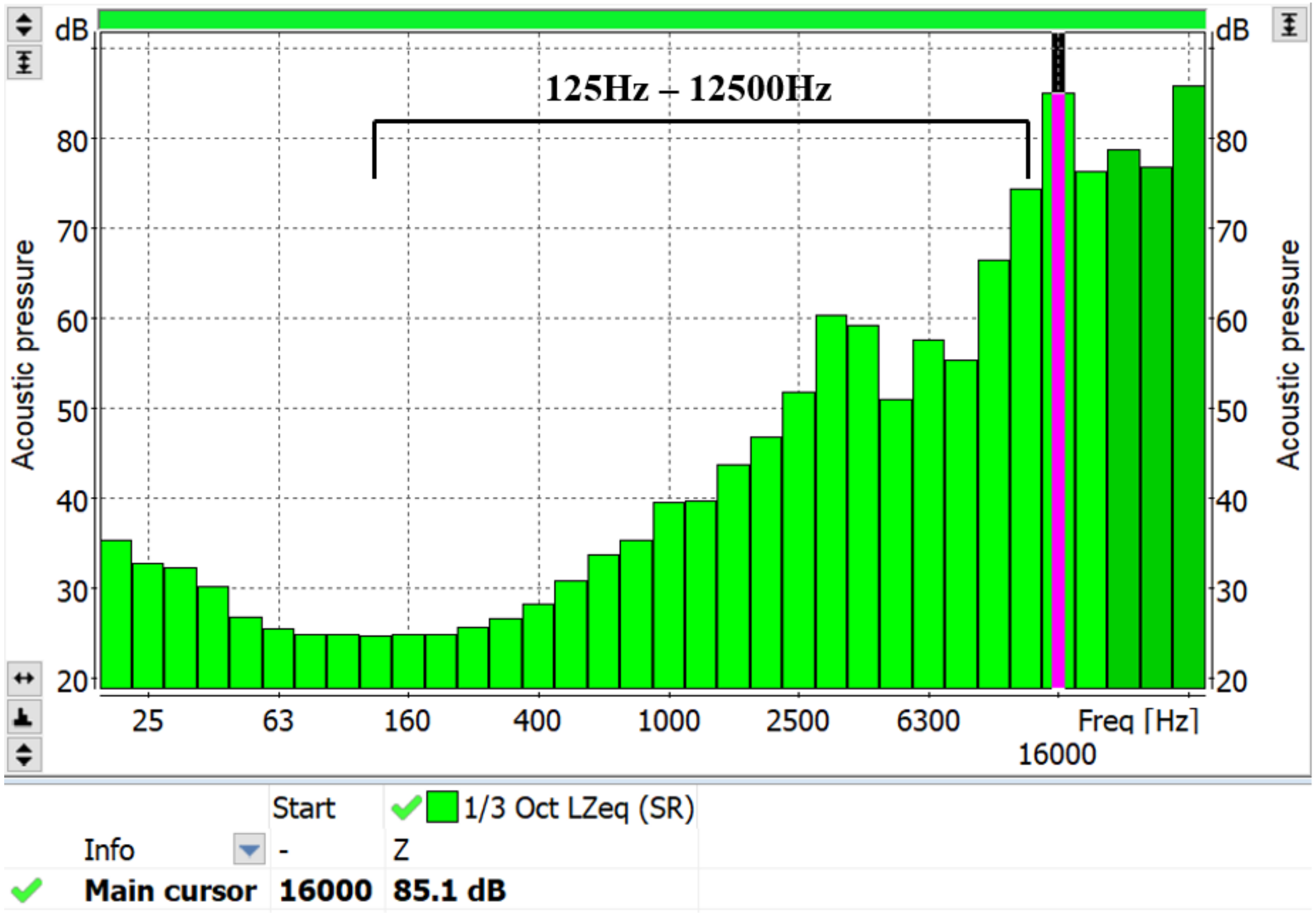
Our experiment



	Start	1/3 Oct LZFeq (SR)
Info	-	Z
Main cursor	**16000**	**87.5 dB**

Audible components – parametric speaker

Our experiment



Implications - headphones

Our experiment

- Headphones are a significant concern:
  - Increasingly used (Henderson et al, 2011)
  - At high volumes, by young people (Herrera et al, 2016; Vogel et al, 2007)
- Also device-agnostic to some extent
- Variations of laptop/phone malware could be adapted
  - Only trigger sound when headphones are connected
- Audio manipulation attack could also succeed with headphones

Implications – parametric speaker

- May be attractive as a portable, low-cost acoustic weapon
- Use in public may constitute significant health risk

Implications – Bluetooth and smart speakers

Our experiment

- Could be used to produce LFN consistent with annoyance
- Smart speaker could be permanently damaged
- ‘Burning-out’ of components could be a fire hazard
- Other models may be vulnerable

Feasibility

Our experiment

- Attacks viable on some devices
  - Any attack/malware capable of arbitrary code execution could deploy this
- Reliant on imperceptibility, susceptibility, exposure duration
- And on no audible components (subharmonics, distortion, etc)
  - Could be attenuated with multiple fade ins/fade outs

Feasibility

Our experiment

- Some attacks require physical/local access, Bluetooth attacks, etc
- Attackers may be more interested in other avenues
  - Espionage, sabotage, financial, etc

Countermeasures

Device-level

- Deshotels, 2014
  - Limit frequency range of speakers
  - Visibly alerting users when speakers are in use
  - Filtering files during processing to remove high/low frequency noise
  - Mobiles: permission restrictions on use of speakers by apps
- Heuristic detection
  - Rarely, if ever, should an application need access to volume levels
  - Maybe muting apps
  - Some legitimate uses for ultrasound (Google Nearby Messages, comms)

Environment-level

Countermeasures

- Monitoring environment for HFN/LFN
  - SLMs (most consumer models won't go that high/low)
  - Requires specialist equipment
  - Android: Ultrasound Detector and Infrasound Detector
  - We used both for our pilot study (Kardous & Shaw, 2014)
  - Modern smartphones *may* be suitable for occupational noise measurement
  - Within limitations of a given device
  - And accepting a certain loss of accuracy

Environment-level

- SoundAlert for HFN detection – PoC only!
- Modified open source application (link below)
- Simple alerts when noise over a threshold is detected

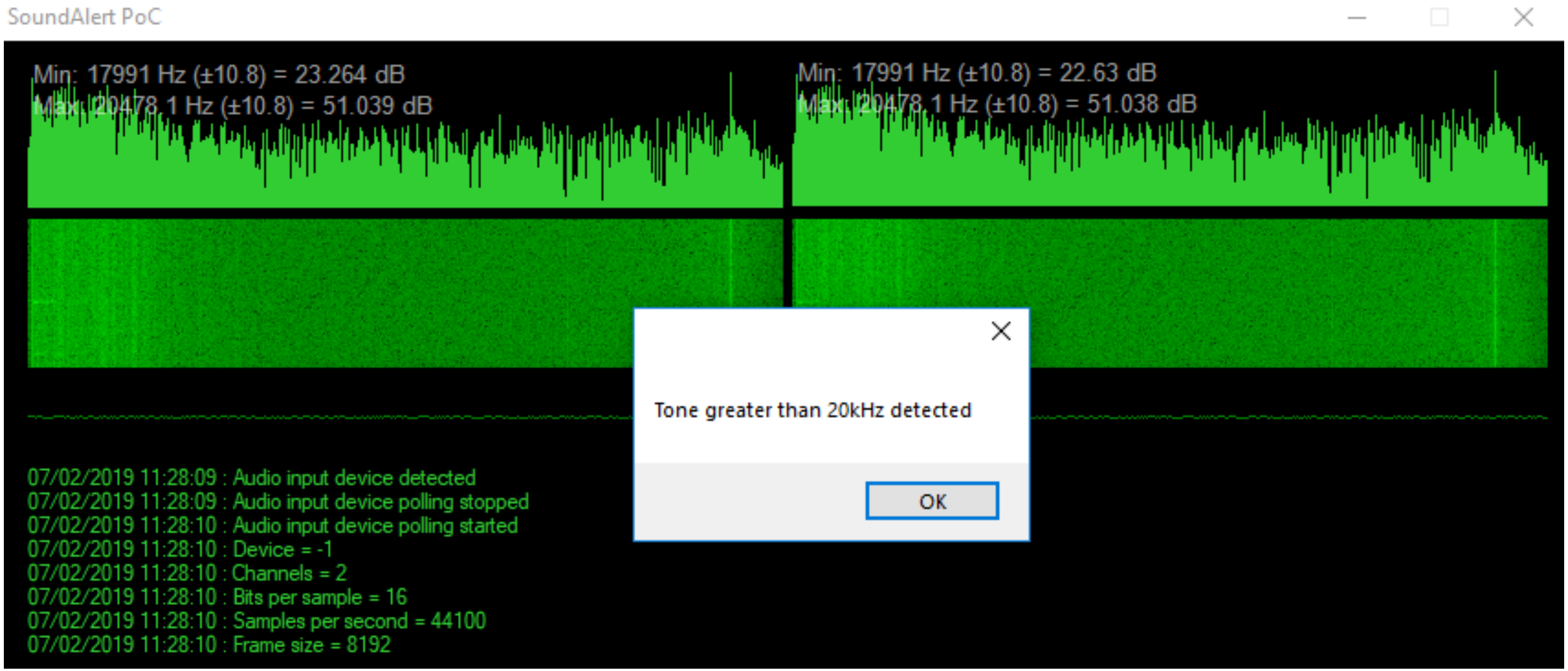
Do not use to evaluate if there is risk of damage or adverse effects, or for safety/compliance assessments (employ a trained professional with appropriate equipment)

https://www.codeproject.com/Articles/22951/Sound-Activated-Recorder-with-Spectrogram-in-C

Environment-level

Countermeasures

- github.com/catz3/SoundAlert-example



https://www.codeproject.com/Articles/22951/Sound-Activated-Recorder-with-Spectrogram-in-C

Policy-level

- Review guidelines:
  - Often inadequate due to methodology
  - Or underestimation of effects
  - Or lack of clarity on implementation outside of occupational contexts
- Employers must comply with applicable legislation
- Should conduct regular checks

Conclusion

Limitations

Conclusion

- Small scale
- Limited number of devices
- Short exposure times
- Constant emission of HFN/LFN may degrade audio equipment
- No human experimentation on perceptibility/susceptibility
  - Frequent limitation of research in this area
  - Ethical and safety concerns have to come first

Future work

- In general, more research needed on the risk of HFN and LFN
- Wider range of equipment, larger-scale, longer durations
- Test overheating effects on other devices
  - Take appropriate safety precautions!
- More work on countermeasures, especially detection
- Ethical restrictions make extrapolation challenging
- Get in touch to discuss more!

Summary

Conclusion

- As digital and physical worlds become more integrated:
  - Attackers may become increasingly interested in leveraging vulns against humans
  - Attack surface likely to grow
  - Attacks are (at the moment) often trivial
  - And may become possible/more effective at scale
  - Lack of consensus for adequate safety guidelines is a challenge
- **However:**
  - Countermeasures are available
  - Real-world consequences are difficult to assess

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Thank you!
Q&A: In corridor

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