Reducing Digitiser Latency for Earthquake Early Warning: New Strategies for Seismic Hardware

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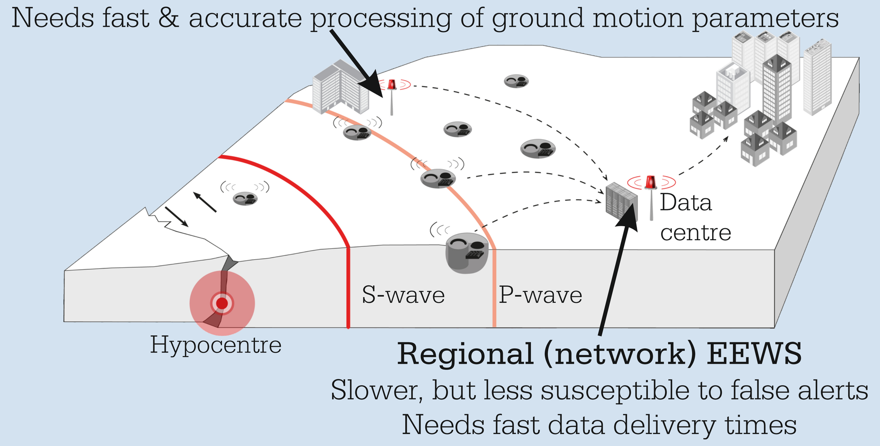
1. Possible delays in existing earthquake early warning systems



> Recent developments and interest in earthquake early warning systems (EEWS) means there is a desire to deliver alerts as fast as possible

> Data delivery time = digital filtering + data packetisation + transmission time

> → Delivery time depends mainly on data-logger type (configuration) and telemetry path (Böse et al., 2009)

> The success of an EEWS is limited by the delivery of waveform data from stations (Brown et al., 2011) - e.g. data latencies are typically >1 s in California networks due to data packetisation (Behr et al., 2015)

- Can we quantify human-controllable sources of latency in EEW hardware & on-board software?
- What advances can be made over existing systems on new seismic hardware to minimise data delivery times and provide the greatest flexibility for EEWS?

2. Digitisation filtering

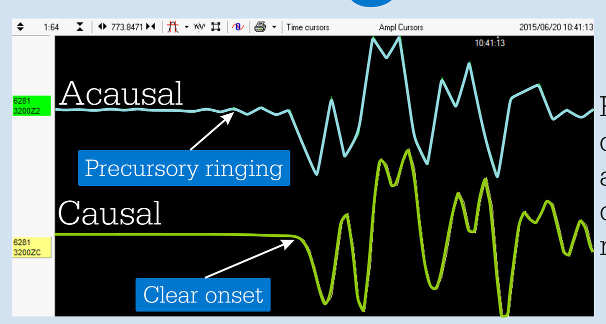
a) Customising decimation filters

> Chain of FIR filters divide by 2, 3, 4 and 5 to decimate to required output sample rate whilst minimising aliasing

> Lower output sample rates increase the time taken for filtering due to greater number of decimation stages - high sample rates require large transmission bandwidth

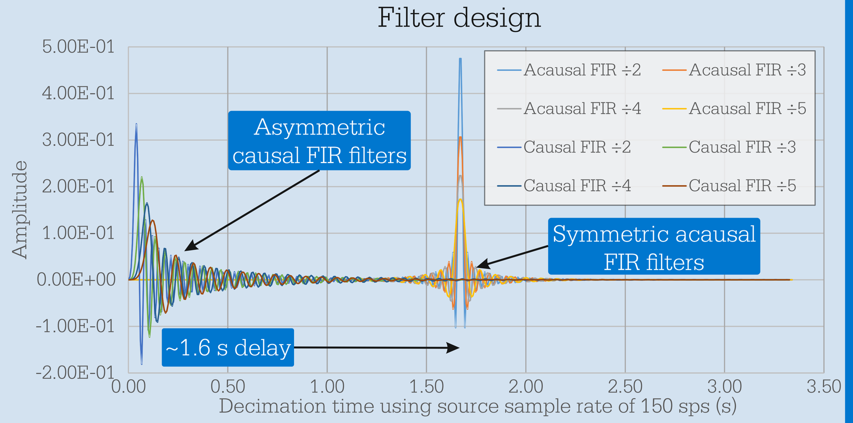
> In addition to standard acausal filters, the Güralp Minimus uses minimum phase causal algorithms

> The Minimus employs a 64-bit DSP to minimise addition of numerical noise during decimation



Filter differences for a M 2.5 event on 2015-06-20 near Coalinga

Filter design



b) Acausal (linear phase) FIR filters

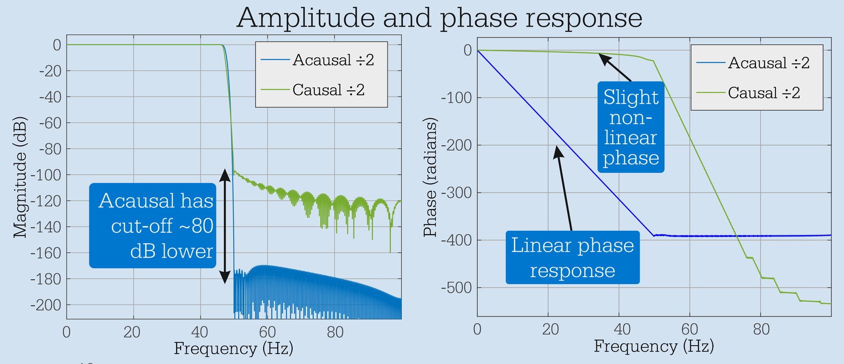
> Typically standard in seismic data-loggers

> Cannot be computed in true real-time

> Gives spurious precursors to seismic onsets (Scherbaum & Bouin, 1997)

> Phase response (especially at low frequencies) is stable (linear)

Amplitude and phase response



c) Causal (minimum phase) FIR filters

> Typically non-standard in seismic data acquisition systems

> Uses only on past and present samples - true real-time acquisition

> Causal filters produce sharper phase onsets - rapid triggering (e.g. STA/LTA) for P-wave detection (Uhrhammer & Nadeau, 2003).

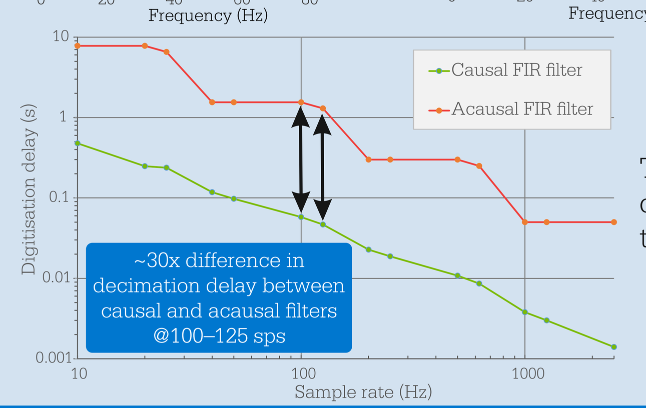
> Güralp Minimus uses asymmetrical causal FIR filters for robust phase response and low latency

> Flat response over the P-wave spectrum of moderate to large earthquake for accurate and rapid magnitude estimation

d) Difference in digitisation latency

> Using causal filters, at sample rates of 100–250 samples per second, decimation can be achieved within 20–60 milliseconds.

> In contrast for the same sample rates, an acausal decimation scheme results in much higher latencies of 0.3–1.6 s.



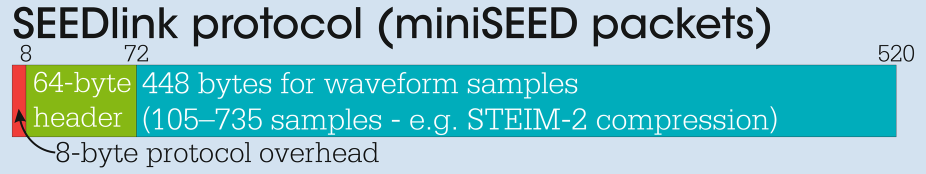
Total decimation time

3. Packetisation: Inherent problems

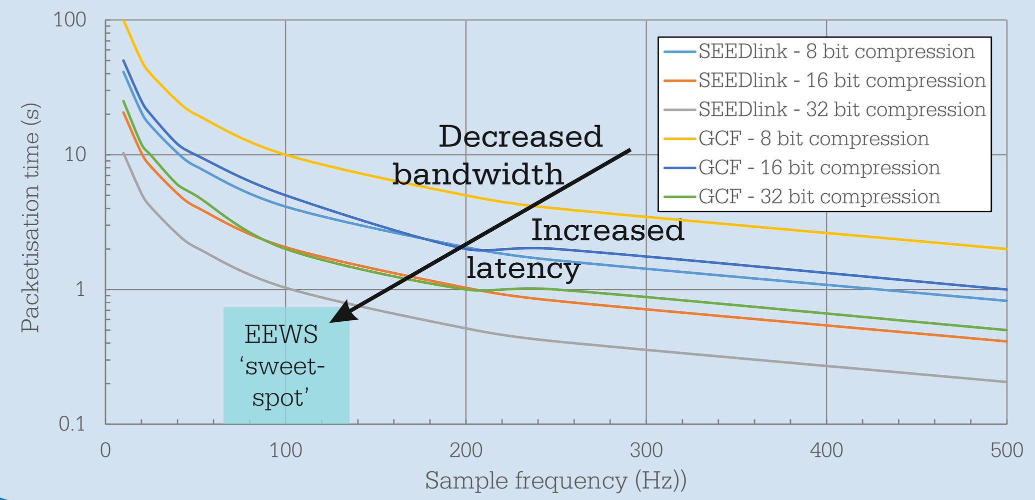
Key problem: currently available data transmission protocols require fixed length packets (takes time to fill)

Scream! protocol (GCF packets)

SEEDlink protocol (miniSEED packets)



Scream! and SEEDlink protocols do not allow transmission of metadata



> Choice of sample rate: trade-off between bandwidth requirement and latency

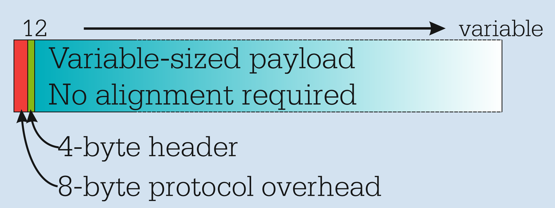
> Small packets require greater CPU load and header overhead

> Increased compression = greater latency (compression depends on signal vs. noise)

> SEEDlink typically results in data delivery latencies of >1 s

4. GDI: a new protocol for EEWS

a) Principle: Flexible packetisation scheme for true real-time transmission



> Dispatches samples as soon as acquired by data-logger

> Per-channel metadata in SEED format

> Lightweight header - channel definitions set up on first connection

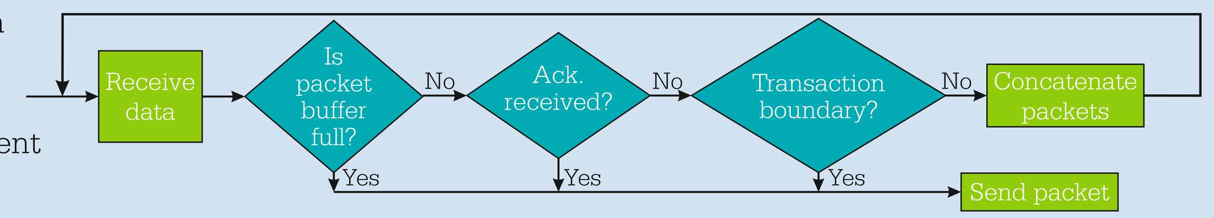
> Machine-readable SoH and direct instrument control

> Simultaneous streaming of digitised ground motion parameters (e.g. PGA)

> Data flow adapts to available bandwidth

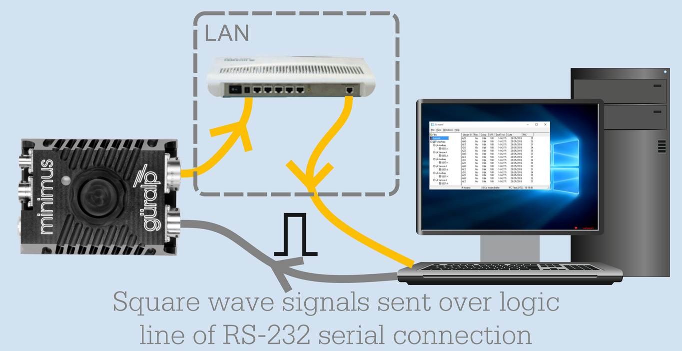
> Adaptation of Nagle's algorithm to improve transmission efficiency

> Does not have to wait for acknowledgment before sending next packet (full-duplex)



b) A simple latency experiment - carried out on the Güralp Minimus

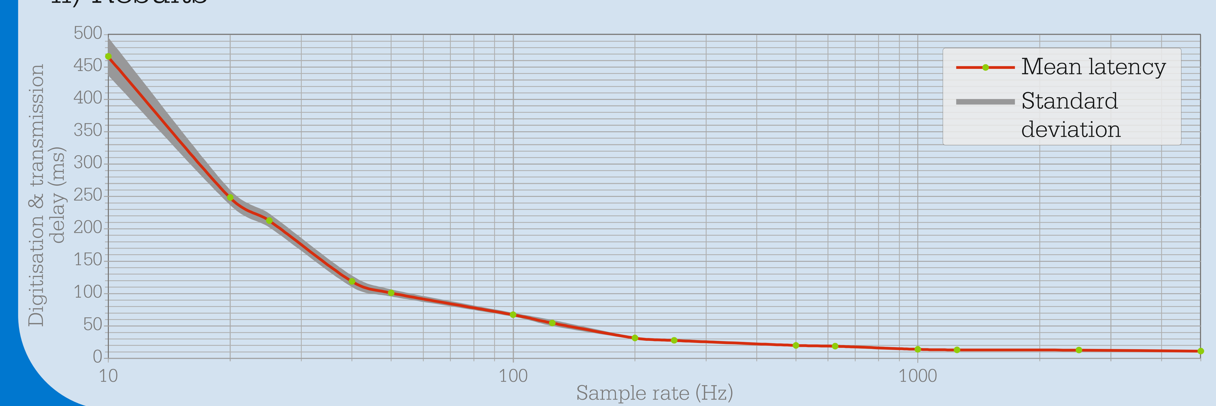
i) Experimental Set-up



Square wave signals sent over logic line of RS-232 serial connection

1. Generate a square wave signal using serial handshake line - period not a multiple of any sample rates - avoids frequency 'beating'
2. Analogue signal digitised and transmitted via sample-by-sample GDI packets over Ethernet (LAN)
3. PC program watches output data - when signal crosses a threshold of 100k counts (2 consecutive samples), compute Δt
4. Random time interval - repeated >200 times

ii) Results



> ~Normally distributed delay times

> Ethernet connection over LAN means that transmission delay is 'best case scenario'

> Mean data delivery delay:
28 ms @ 200 sps
49 ms @ 125 sps
63 ms @ 100 sps

> Sample-by-sample GDI transmission typically requires bandwidth of 6.4 kbps @100 sps (excl. TCP overhead)

5. Planned future developments: Hybrid on-site/network warning

a) On-site warning parameters

> On-site early warning can reduce the radius of the alert 'blind' zone (Wu and Kanamori, 2005)

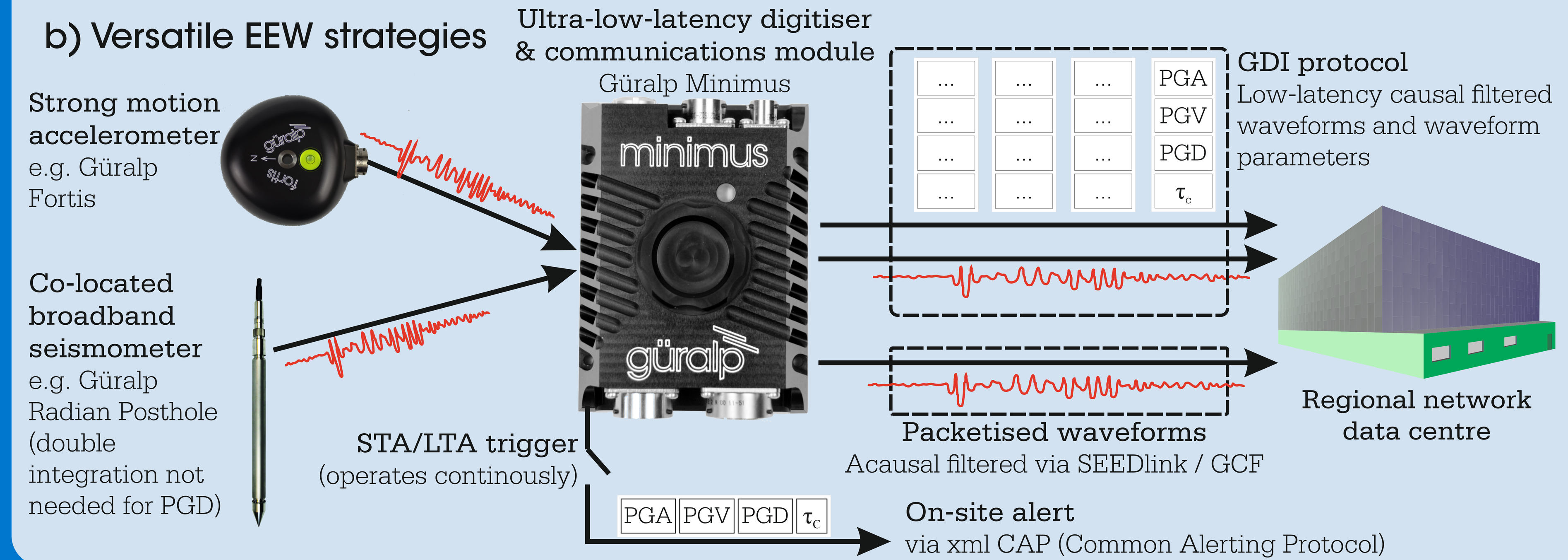
> On-site streaming of single parameters could reduce the load on telemetry during a seismic event

> Wu and Kanamori (2005) showed that faster warnings can be issued by using a hybrid on-site / regional system (streaming ground motion parameters to a regional data centre)

> Real-time streaming of ground motion parameters from local to more distal sites can help to confirm or cancel on-site alerts (Zollo et al., 2010) - possible to communicate triggers across network via GDI

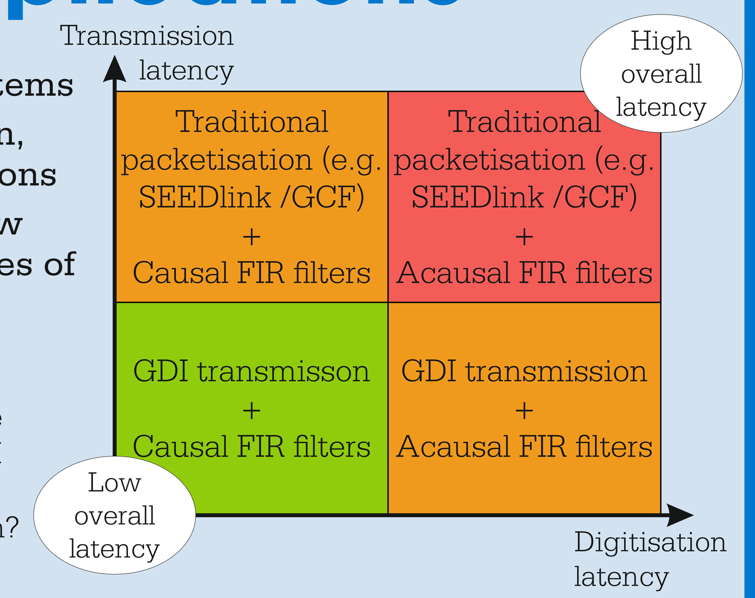
Dominant P-wave period, τ_c	Peak P-wave Ground Displacement	Peak Ground Velocity, PGV	Peak Ground Acceleration, PGA
$\tau_c(t_0) = 2\pi\sqrt{\frac{\int_0^{t_0} u^2(t)dt}{\int_0^{t_0} \dot{u}^2(t)dt}}$; $M_W = b\cdot\log(\tau_c) + a$; Kanamori et al. (2005)	$\log(PGV) = b\log(Pd) + a$ Wu et al. (2007); $\log(PGD_i^{\delta km}) = A' + B'M$ Zollo et al. (2006)	Used to verify and update predictions made using Pd	Update magnitude/distance estimations from attenuation relationships

b) Versatile EEW strategies



6. Summary and implications

1. Currently available off-the-shelf data-loggers can introduce significant latency (seconds) into earthquake early warning systems
2. SEEDlink is the de-facto standard for real-time data transmission, but is inflexible and has high latency for early warning applications
3. Using minimum-phase filters and GDI transmission protocol, new Güralp hardware is capable of achieving rapid data delivery times of 30–70 ms (over a LAN) for sample rates of 100–200 sps



Ongoing research and development

> Latency will increase when the network is highly loaded (is sample-by-sample always possible?). Future work needed to understand true latencies using GDI transmission over realistic regional network infrastructure

> Causal filters fast but phase non-linear - what is the effect on e.g. τ_c estimation?

Key applications for the EEW community

- We are working in partnership with Gempa to develop a GDI plug-in for the CAPS module of SeisComPro (handles multi-parametric streams in a unified protocol)
- The source code of GDI will be freely licensed so that network operators and instrumentation vendors can incorporate the protocol into their systems
- Both causal and acausal filters can be simultaneously used on the Güralp Minimus (no latency - quality trade-offs)
- We are keen to work closely with the EEW community to include 'must-have' features on our seismic hardware

For a full hands-on demonstration of the low latency mode on the Güralp Minimus, visit our Booth (544) in the Exhibit Hall

References

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