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Sources of Latency and Associated Design Trade-offs in Earthquake Early Warning Systems

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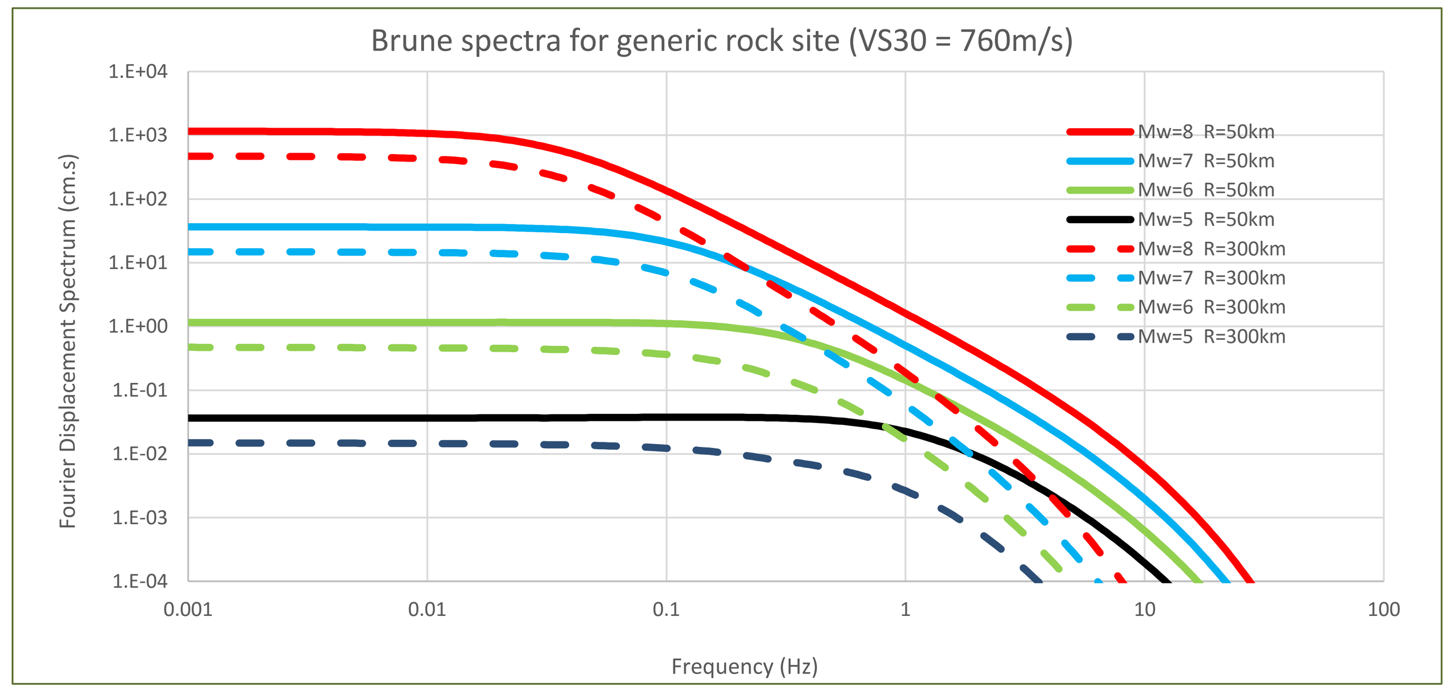
SUMMARY

Low latency is a key contributor to the success of an Earthquake Early Warning (EEW) system. There are several points where delay is introduced between the instant in time that a digitizer produces a set of samples across its analog sensor channel inputs and the point at which the corresponding data reaches its destination for EEW. These points of delay arise out of software, mathematical, and networking as well as physical constraints imposed upon the digitizer and associated communication systems. System designs must account for tradeoffs between latency and resource (CPU) utilization, which has an effect on power consumption, and communication network bandwidth. Designers of seismological instrumentation used for EEW deployments must keep these trade-offs in mind and make careful implementation choices to minimize delay. System integrators and network operators must be fully aware of latency and its contributors in order to make the right configuration choices when commissioning EEW systems to ensure the lowest possible latency without compromising the accuracy of the early warning data product.

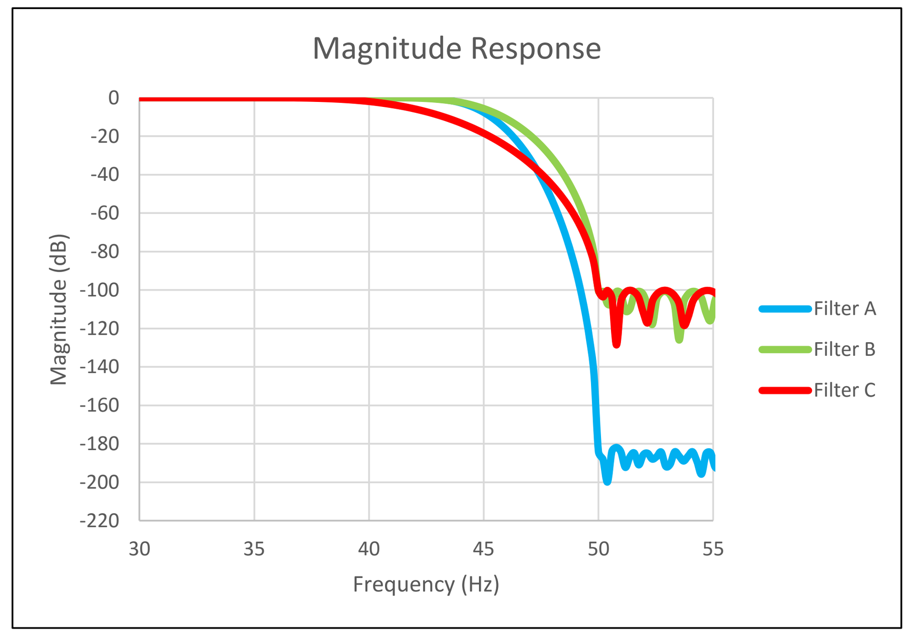
DIGITIZER - DECIMATION

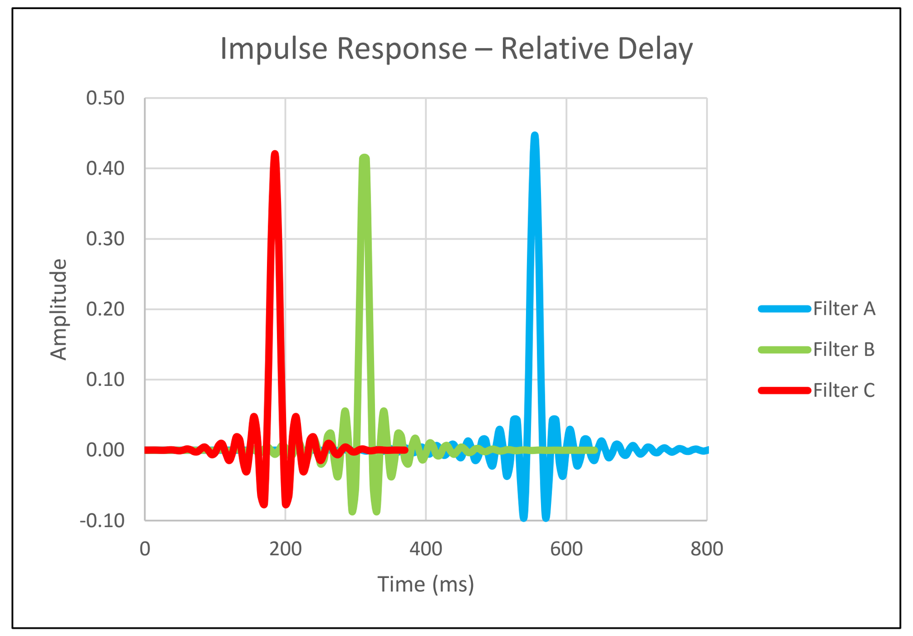
ADC hardware initially samples ground motion channel analog signals at high sample rates. Choices made in decimation filter design yield trade-offs to be made between latency, signal quality, digitizer resource consumption (power, storage), and network speed requirements

- EEW systems must make a rapid estimate of earthquake magnitude at P-wave arrival time. Based on work done by Nakamura in 1988, Allen and Kanamori (2003) showed that the predominant period (τ^p, also known as τ_p^{max}) obtained from measurements of low frequency energy during the first 3 seconds after P-wave arrival is a good predictor of the magnitude of small (magnitude 3-5) to large (magnitude > 4.5) earthquakes. Kanamori (2005) showed a similar correlation to magnitude with an average period (τ_c) of ground motion calculation
- Large earthquake spectra of interest for local and regional events is < 10 Hz

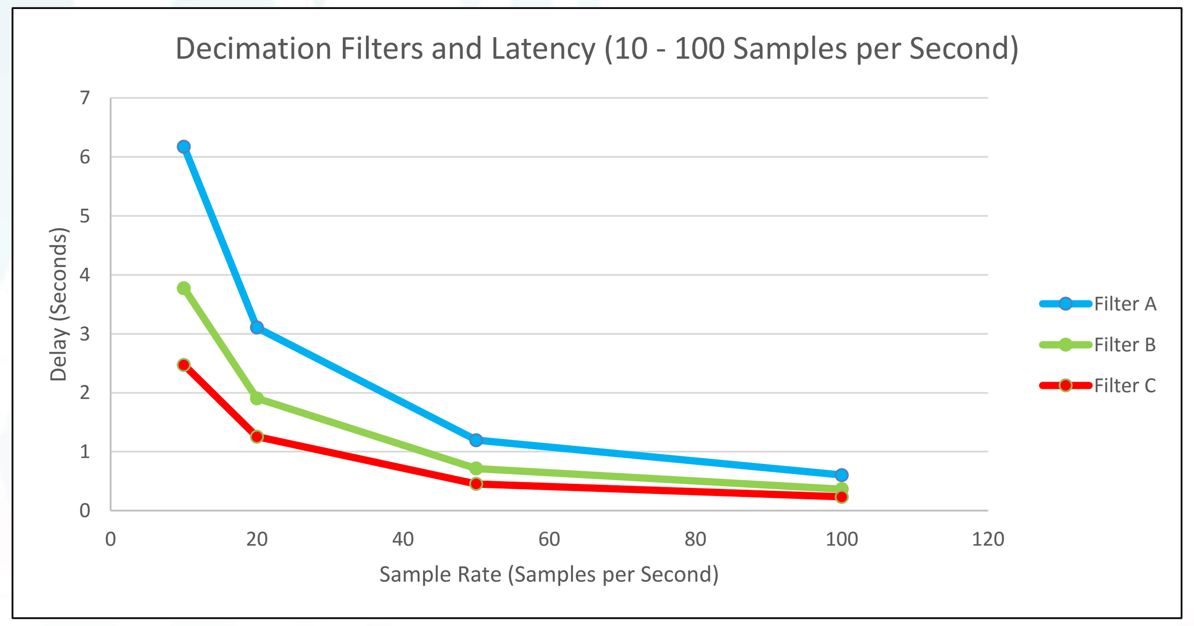


- Higher digitizer output sample rates yield a wider passband (Nyquist) and reduce latency, but result in sustained higher digitizer processing activity (which affects power consumption) and requires higher network streaming data rates
- Decimation filter design choices can reduce latency at the cost of signal fidelity at the high end of the passband, but not sacrifice magnitude estimation capability





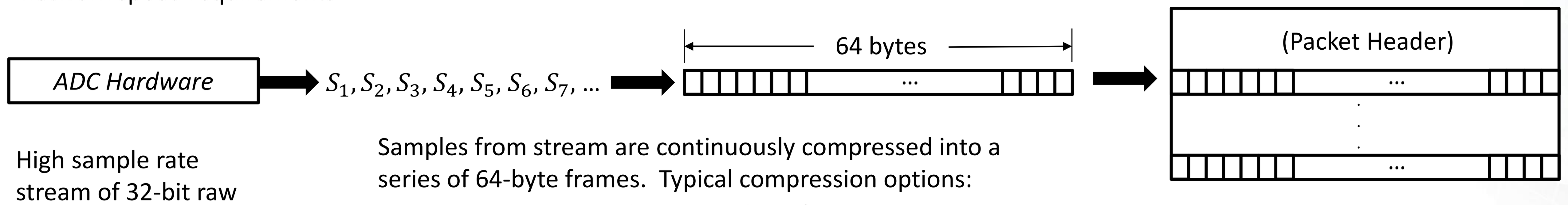
Decimation filters A, B, and C illustrate the effects of filter design in the frequency and time domains



- Decimation filters can be designed to optimize performance for the given use case. EEW systems must favor reduced latency over signal quality, but retain flat response for the spectra of interest
- Sample rates <= 100 Hz using low-latency decimation filters are quite adequate for EEW systems
- Lower sample rates (<< 100 Hz) provide more than sufficient passband width for the P-wave spectra of interest for magnitude prediction, however excessive delay is introduced. The choice of sample rate must be made in the context of digitizer configuration options for data compression and packet size

DIGITIZER – DATA COMPRESSION AND PACKET SIZE

Choices made in digitizer configuration yield trade-offs to be made between latency and digitizer resource consumption (power, storage), and network speed requirements

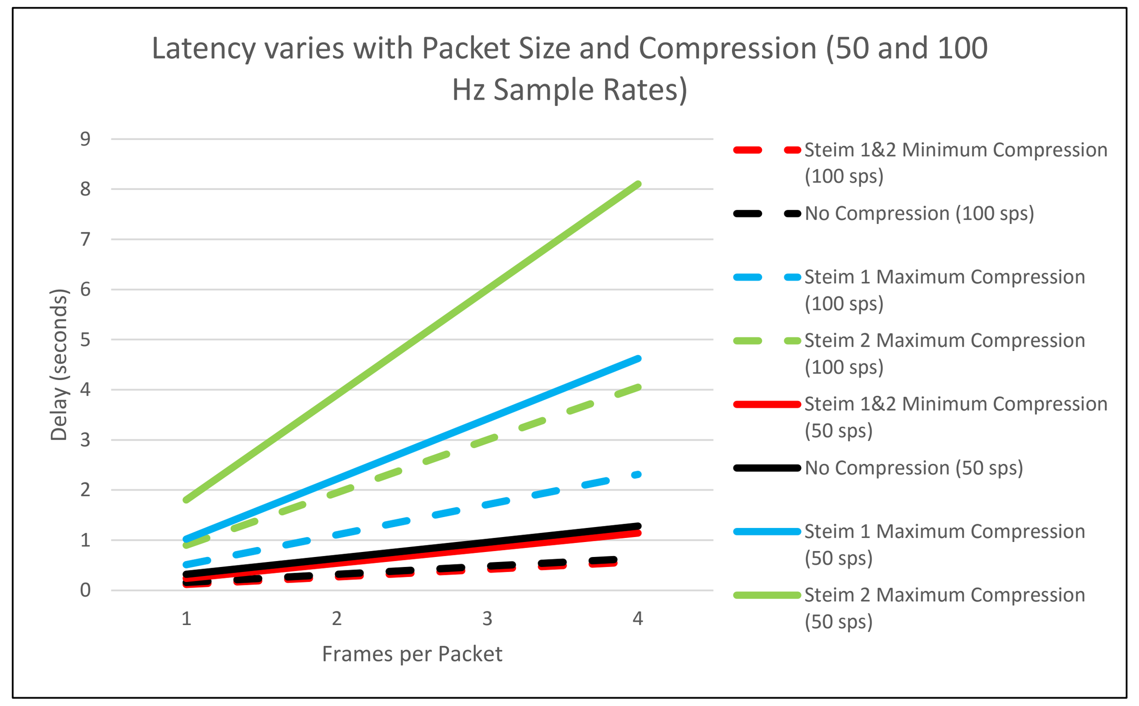


High sample rate stream of 32-bit raw samples are decimated and low-pass filtered

Samples from stream are continuously compressed into a series of 64-byte frames. Typical compression options:

- Steim1: 13-52 samples in a 64-byte frame
- Steim2: 13-91 samples in a 64-byte frame
- Uncompressed: 16 x 4 byte samples in a 64-byte frame

A configurable number of frames are included in each recorded (and streamed) packet



- Delays incurred by large and/or more highly-compressed packets are excessively long for use in earthquake early warning deployments.
- A high sample rate and small packets result in a high packet rate as well as a loss of storage efficiency due to higher overhead.
- The consequences of a high packet rate also include higher digitizer power consumption arising from higher CPU load, as well as less efficient storage due to a higher ratio of overhead to seismic sample data.
- Note that compression will decrease at the onset of the event since the algorithms are difference-based. Larger amplitude ground motion increases differences, reduces compression, and therefore decreases delay.

NETWORK STREAMING

- Cellular radio-based communication plays a key role in the EEW streaming data path through regions with the required infrastructure. Data rates are sufficiently high, typically resulting in delays of several dozen milliseconds, and the packet-based nature of the network allows for cost efficient transmission of data.
- Other communication technologies (e.g. satellite) can be employed for very remote EEW monitoring stations, but radio wave propagation distances can be large and additional sources of delay exist that result in extra complications to achieve latency objectives.
- Consideration must be given to the consequences of using a streaming-based protocol (i.e. Transmission Control Protocol -- TCP) versus a datagram-based protocol (i.e. User Datagram Protocol – UDP). Delays arise from TCP from its flow control mechanism and careful network design is therefore required, particularly when satellite communication is involved.

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