Mega Hertz, Mega Samples, Mega bits, Mega Confusing

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@robinlgetz
Focus of this talk

- **Grammar**
  - grammar is the set of structural rules governing the composition of clauses, phrases and words in a natural language.

- **Numbers**
  - A number is a mathematical object used to count, measure, and label.
    - [https://en.wikipedia.org/wiki/Number](https://en.wikipedia.org/wiki/Number)
  - Numbers in Science
  - Numbers in Mathematics

Constituency-based parse tree

John hit the ball.

Tjo3ya - Own work, [CC BY-SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/)
Back to basics

Nouns, Verbs & Adjectives
Ms. Kittredge’s
Grade 5
2005/06

Nouns are thin
flower

https://www.umass.edu/pvnet/imagery_files/TeacherProjectsAug/kittredge.ppt
What are adjectives

Adjectives are words that descri

This bowl is red and shiny.

https://www.umass.edu/pvnet/imagery_files/TeacherProjectsAug/kittredge.ppt
The ADALM-PLUTO has a maximum sample rate of \( \frac{1}{61,440,000} \) Hz.
Numbers in Science vs. Numbers in Math

This lesson is designed to help provide students with an understanding of how numbers are used in science. This differs from the way you are used to thinking about numbers. For example, while every digit that comes from a counting or calculation and the numbers we deal with in the world, it is almost always necessary to account for every digit that comes from your calculations in a class.

Making a Measurement

The key to understanding numbers in science is realizing that there is a fundamental difference between numbers in science and numbers in math. Since a fundamental part of science is estimation involved in making a measurement.

The reason for this is that no measurement is exact. Every measurement has an uncertainty associated with it. That is, no measurement is perfect. The uncertainty is a measure of how far off we are from the true value.

For example, on the previous slide, we might have said that we saw 199 ± 1 ml. That means the measured value was 200 ml, but we had some uncertainty in the measurement. The uncertainty is a measure of how far off we are from the true value.

Reporting a Measurement

Because we encounter numbers all the time, it is important to include only the measurement, we should not report the uncertainty.

The number of digits reported in any measurement is significant. It is paramount that all scientists: exactly one estimated digit in a measurement, exactly one estimated digit is reported.

While it is preferable to record actual uncertainty, an implicit rule is that your uncertainty is ± one digit.

Therefore, a mass of 68.5 kg is implicitly 68.5 ± 0.5 kg.

Significant Figures

Because scientists have agreed on a convention that exactly one estimated digit is significant, one can assume that the smallest recorded digit corresponds to the estimate.

Consider the following examples:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Estimated Digit</th>
<th>Implied Uncertainty</th>
<th># of Sig Figs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 x 10^{2} kg</td>
<td>0 in the 10^{2} kg place</td>
<td>2.0 ± 0.1 x 10^{2} kg</td>
<td>2</td>
</tr>
<tr>
<td>384,400 km</td>
<td>4 in 100 km place</td>
<td>384,400 ± 100 km</td>
<td>4</td>
</tr>
<tr>
<td>13 billion years</td>
<td>3 in the billion years place</td>
<td>13 ± 1 billion years</td>
<td>2</td>
</tr>
<tr>
<td>3.00 x 10^{8} m/s</td>
<td>0 in the 10^{8} m/s place</td>
<td>3.00 ± 0.01 x 10^{8} m/s</td>
<td>3</td>
</tr>
<tr>
<td>8 planets in Ss</td>
<td>None</td>
<td>None</td>
<td>Unlimited</td>
</tr>
<tr>
<td>365.242199 days</td>
<td>9 in the 10^{1} days place</td>
<td>365.242199 ± 0.000001 days</td>
<td>9</td>
</tr>
</tbody>
</table>

Software Defined Radio Audience

- Mathematicians
- Scientists
- People who are bad at grammar
Software Defined Radio mix of Math & Science

- Communications Theory is:
  - largely mathematics and statistics
  - everything is a float
    - infinite precision
  - Everything is exact, no units
- Digital Hardware
  - everything is fixed int
    - 18-bit numbers, fixed point fractional
  - Everything is exact, no errors in clocks
- RF Hardware
  - makes up units
    - dB is relative to what?
  - Doesn’t want to say how bad the hardware is, so leaves out uncertainty
- Software
  - Everything is a buffer/vector
- Each discipline feels their work is obvious, and doesn’t use units

Communications theory

\[ s[2\ell N + n] = \frac{1}{2N} \sum_{k=0}^{2N-1} p_k[\ell] e^{j(2\pi n k / 2N)} \]
RF to Antenna

What does Bandwidth mean?
Bandwidth

- Bandwidth is the difference between the upper and lower frequencies in a continuous band of frequencies. It is typically measured in hertz, and depending on context, may specifically refer to passband bandwidth or baseband bandwidth.

- The frequency range or bandwidth over which an antenna functions well can be very wide.

```
SPECIFICATIONS

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>Frequency Range: 824–894/1710–2170MHz or 880–960/1710–2170MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
</tr>
<tr>
<td>Gain</td>
<td>2dBi (Zenith)</td>
</tr>
<tr>
<td>V.S.W.R (min)</td>
<td>&lt;2.5</td>
</tr>
<tr>
<td>Impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Connector</td>
<td>SMA right Male</td>
</tr>
<tr>
<td>Environmental</td>
<td>Operating Temperature: -40°C to +85°C</td>
</tr>
<tr>
<td></td>
<td>Vibration: 10 to 55Hz with 1.5mm amplitude 2 hours</td>
</tr>
<tr>
<td></td>
<td>Environmentally Friendly: ROHS Compliant</td>
</tr>
</tbody>
</table>
```
What is Digital PreDistortion?


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DPD - Digital Pre-Distortion

- Feed-forward approach
  - Simpler
  - Does not account for part-to-part or temp variation

- Feed-back approach
  - More complicated
  - Adapts to changing conditions
  - Typically requires 5x signal bandwidth observation Rx
# Air Interface

<table>
<thead>
<tr>
<th>LTE Bandwidth Set (MHz)</th>
<th>Occupied RF Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>1.08</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>15</td>
<td>13.5</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
</tr>
</tbody>
</table>

- **Channel Bandwidth**: Represents the total bandwidth allocated for transmission.
- **Occupied Bandwidth**: The actual bandwidth used for data transmission.
- **Guard Band**: The buffer space between channels to avoid interference.
- **Synthesized Bandwidth**: The bandwidth that can be generated or synthesized digitally.
ACLR - Adjacent Channel Leakage Ratio

- ACLR is the ratio of the mean Tx channel power to the mean adjacent or alternate channel power (ACP).
- Power Amplifier is primary source of ACP due to its nonlinearities.
- Signal pre-distortion techniques are employed to reduce the ACP.
- 3GPP LTE Spec: 45 dB.
Analog Signals

- **Double-sideband (DSB)** occupies $2M$ bandwidth in $\omega > 0$, even though all the information is contained in $M$.

- **Single-sideband (SSB)** occupies $M$ bandwidth in $\omega > 0$.

http://stellar.mit.edu/S/course/6/sp08/6.003/courseMaterial/topics/topic1/lectureNotes/Lecture__15/Lecture__15.pdf
Antenna to Interface

SDR Hardware
Receiver Noise

- Receiver Total Noise
  - Combination of RF section and A/D
  - RF section shaped by anti-aliasing filter
  - A/D noise typically flat

- Calculation Method
  - Convert to common units
  - Noise added in units of power

- Noise Limited Dynamic Range
  - Signal – Noise Power in Channel BW

A/D Noise\( (dBm / Hz) = A/D\) Full Scale \( (dBm) + A/D\) Noise Density \( (dBFS / Hz) \)

Total Noise\( (dBm / Hz) = 10 \log_{10} \left( \frac{10^{\frac{\text{Receiver Noise} (dBm / Hz)}{10}} + 10^{\frac{\text{A/D Noise} (dBm / Hz)}{10}}}{} \right) \)

A/D Sensitivity Loss (dB) = Total Noise\( (dBm / Hz) \) – Receiver Noise\( (dBm / Hz) \)
Receiver Specs – Bandwidth / Frequency Range

- **Bandwidth**
  - Can refer to
    - Amount of spectrum that can be used at any instant (Instantaneous BW)
    - Channelized BW – BW passed through digital filtering
    - Frequency range that can be received

- More instantaneous bandwidth allows
  - more users/channels
  - faster sweep times (fewer steps)

- More instantaneous BW means more potential interference
  - Sometimes leads to selectable BW

- Higher BW requires higher sample rate on ADC
  - Ex: To achieve 1GHz BW, sample ADC at >2GSPS

Simply stated, the Nyquist criterion requires that the sampling frequency be at least twice the highest frequency contained in the signal, or information about the signal will be lost. Harry Nyquist's classic Bell System Technical Journal article of 1924. (He was 35)
SDR Σ-Δ ADC noise shaping

\[
\frac{30.72}{2} \times 1.25 \approx 19.366
\]
Analog filtering is easier with higher sample rates
SDR Σ-∆ ADC noise shaping

\[
\frac{30.72}{2} \cdot 1.25 \approx 19.366
\]
Analog filtering is easier with higher sample rates
Basic DPD System

4.5 MHz Occupied Bandwidth

25 MHz Synthesized Bandwidth

25 MHz

Coupler

PA

25 MHz

38.4 MSPS

25 MHz

25 MHz Synthesized Bandwidth

38.4 MSPS

25 MHz

Delay Estimation & Retiming

DPD Adaptation

DPD Control and Updater

Predistorter

Interpolation 5x

LTE 5 Modem Tx

38.4 MSPS

25 MHz

7.68 MSPS

4.5 MHz

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# LTE Specifications

<table>
<thead>
<tr>
<th>Channel Bandwidth MHz</th>
<th>Occupied Bandwidth MHz</th>
<th>MSPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>1.08</td>
<td>1.92</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>3.84</td>
</tr>
<tr>
<td>5</td>
<td>4.5</td>
<td>7.68</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>15.36</td>
</tr>
<tr>
<td>15</td>
<td>13.5</td>
<td>23.04</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>30.72</td>
</tr>
</tbody>
</table>
Interface: CMOS or LVDS

- Runs at 2 – 4 x sample rate
- DDR (or not)?
- Mega bits per second transfer
- MHz Clocks
Interface: JESD204

---

**Table 8. Example Receiver Interface Rates (Other Output Rates, Bandwidth, and JESD204B Lanes Also Supported)**

<table>
<thead>
<tr>
<th>Bandwidth (MHz)</th>
<th>Single-Channel Operation</th>
<th>Dual-Channel Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output Rate (MSPS)</td>
<td>JESD204B Lane Rate (MSPs)</td>
</tr>
<tr>
<td>80</td>
<td>122.88</td>
<td>4915.2</td>
</tr>
<tr>
<td>100</td>
<td>153.6</td>
<td>6144</td>
</tr>
<tr>
<td>100</td>
<td>245.76</td>
<td>9830.4</td>
</tr>
<tr>
<td>200</td>
<td>245.76</td>
<td>9830.4</td>
</tr>
</tbody>
</table>

---

**Figure 431. Receiver and Observation Receiver Datapath Filter Implementation**

Transport

512 MBytes on Pluto SDR
Linux kernel continuous memory allocator; 128MBytes for Tx, and 128MBytes for Rx
Takes about ~4 seconds to transfer 128 Mbytes over USB 2.0

480 Mbps * 8/10 / 8bits/byte = 48 MB/s
48 Mbytes/s * USB overhead * libiio overhead = ~ 32 MB/s

USB 2 is half duplex, so full duplex is ½ the datarate

<table>
<thead>
<tr>
<th>MHz</th>
<th>MSPS</th>
<th>MB/s single channel</th>
<th>MByte/s (I/Q)</th>
<th>External Memory (Mbytes)</th>
<th>Seconds of RF Data in Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>61.44</td>
<td>122.88</td>
<td>245.76</td>
<td>128</td>
<td>0.521</td>
</tr>
<tr>
<td>18</td>
<td>30.72</td>
<td>61.44</td>
<td>122.88</td>
<td>128</td>
<td>1.042</td>
</tr>
<tr>
<td>9</td>
<td>15.36</td>
<td>30.72</td>
<td>61.44</td>
<td>128</td>
<td>2.083</td>
</tr>
<tr>
<td>4.5</td>
<td>7.68</td>
<td>15.36</td>
<td>30.72</td>
<td>128</td>
<td>4.167</td>
</tr>
<tr>
<td>2.25</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>128</td>
<td>8.333</td>
</tr>
<tr>
<td>.200</td>
<td>0.520</td>
<td>1.04</td>
<td>2.08</td>
<td>128</td>
<td>61.44</td>
</tr>
</tbody>
</table>
### Transport

**ADRV9009-ZU11EG**

<table>
<thead>
<tr>
<th>MHz</th>
<th>MSPS</th>
<th>MB/s single channel</th>
<th>MByte/s (I/Q)</th>
<th>Number of Channels</th>
<th>External Memory (Mbytes)</th>
<th>Seconds of RF Data in Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>245.76</td>
<td>491.52</td>
<td>983.04</td>
<td>1</td>
<td>4096</td>
<td>4.167</td>
</tr>
<tr>
<td>200</td>
<td>245.76</td>
<td>491.52</td>
<td>983.04</td>
<td>8</td>
<td>4096</td>
<td>0.520</td>
</tr>
<tr>
<td>100</td>
<td>122.88</td>
<td>245.76</td>
<td>491.52</td>
<td>1</td>
<td>4096</td>
<td>8.333</td>
</tr>
<tr>
<td>100</td>
<td>122.88</td>
<td>245.76</td>
<td>491.52</td>
<td>8</td>
<td>4096</td>
<td>1.042</td>
</tr>
<tr>
<td>56</td>
<td>61.44</td>
<td>122.88</td>
<td>245.76</td>
<td>1</td>
<td>4096</td>
<td>16.667</td>
</tr>
<tr>
<td>56</td>
<td>61.44</td>
<td>122.88</td>
<td>245.76</td>
<td>8</td>
<td>4096</td>
<td>2.083</td>
</tr>
</tbody>
</table>

4096 MB (PS) + 4096 MB (PL) on ADRV9009-ZU11EG

Takes about ~16 seconds to transfer 4096 Mbytes over USB 3.0

PCIe 3.0 / x8 lanes = 7.88 Gbytes/s
Accuracy – significant digits

**BBPLL Clock Rate**

\[ BBPLL \text{ Clock Rate} = F_{REF} \times \left[ N_{\text{INTEGER}} + \frac{N_{\text{FRACTIONAL}}}{2088960} \right] \]

**ADC Clock Rate**

\[ \text{ADC Clock Rate} = \frac{BBPLL \text{ Clock Rate}}{2^{\text{BBPLL Divider}[2:0]}} \text{ (decimal)} \]

- **F_{REF}** = Reference Clock Frequency
- **N_{\text{INTEGER}}** = 8-bit Integer word
- **N_{\text{FRACTIONAL}}** = 20-bit Fractional word
- Smallest Step based on 40 MHz Ref Clock
  - 40.0000 MHz * 1/2088960 = 19.15 Hz
- BBPLL Divider is valid from 1 through 6
  - 64 = 0.29919194240196078431372549019608 Hz step size

**F_{RFPLL}**

\[ F_{RFPLL} = F_{REF} \times \left( N_{\text{Integer}} + \frac{N_{\text{Fractional}}}{8,388,593} \right) \]

- **F_{REF}** = Reference Clock Frequency
- **N_{\text{INTEGER}}** = 11-bit Integer word
- **N_{\text{FRACTIONAL}}** = 23-bit Fractional word
- Smallest step based on 40MHz Ref Clock
  - 40.0000 MHz * 1/8,388,593 = 4.77464117084585035343684039079 Hz
- 2.400 GHz with a 40.0000 MHz Ref clock is integer **N_{\text{INTEGER}} (60)** and **N_{\text{FRACTIONAL}} (0)**.
- 2.400 GHz with a 39,999,898 Hz REF CLK, is not possible.
  - **N_{\text{INTEGER}} (60)** and **N_{\text{FRACTIONAL}} (1283.45)**
  - **N_{\text{INTEGER}} (60)** and **N_{\text{FRACTIONAL}} (1283) = 2,399,999,997.816079**
  - **N_{\text{INTEGER}} (60)** and **N_{\text{FRACTIONAL}} (1284) = 2,400,000,002.584447**
Stability

- **Accuracy**
  - The degree of conformity of a measured or calculated value to some specified value or definition

- **Initial accuracy**
  - Due to manufacturing tolerance
    - Can be calibrated out (initial settings)

- **Aging**
  - The change in frequency with time due to internal changes in the oscillator.

- **Drift**
  - The change in frequency with time that one observes in an application.

- **Temp**
  - The change in frequency with time that one observes due to temperature changes.
    - Is very repeatable between runs

- **Doppler shift due to mobility**
  \[ f_D = \frac{v_r f}{c} \cos \alpha; \]
  - 6 GHz LO, 150 kph = 0.139 ppm offset
  - 1 GHz LO, 450 kph = 0.417 ppm offset

\[ \Delta T = \frac{1}{2} at^2 \]
\[ \Delta T = \text{Time Error} \]
\[ a = \text{aging} \]
\[ t = \text{Elapsed Time} \]

\(v_r\) is the relative speed between the transmitter and the receiver
\(f\) is the carrier frequency
\(\alpha\) is the angle of the velocity vector
\(c\) is the speed of light

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Accuracy - Magnitude

PCB Component frequency wide tuning range (70 – 6000 MHz) (Close to datasheet specs)
Accuracy - Magnitude

- dBm
  - sometimes $\text{dB}_mW$ (or decibel-milliwatts) is unit of level used to indicate that a power ratio is expressed in decibels (dB) with reference to one milliwatt (mW)

- dBFS
  - Power ratio with respect to full-scale (whatever that is)

- dB
  - ratio with respect to something

- Factory calibrations are necessary to limit the amount of variation seen across a large quantity of circuit boards.
- Some calibrations are used to increase the accuracy of the device, while others are needed to calibrate non-linearities of external components in the RF front-end.

<table>
<thead>
<tr>
<th>(Your) Factory Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Internal DCXO (AFC tune range)</td>
</tr>
<tr>
<td>2 TX RSSI (TX Monitor)</td>
</tr>
<tr>
<td>3 RX RSSI (Absolute Power Correlation)</td>
</tr>
<tr>
<td>4 RX GM / LNA Gain Step Error</td>
</tr>
<tr>
<td>5 TX Power out Vs TX attenuation</td>
</tr>
<tr>
<td>6 TX Power out Vs Frequency</td>
</tr>
</tbody>
</table>
Samples -> Symbols
Sampling at the right time
Sampling at the right time

**Transmitter**
- Signal Generation
- RC Filter
- SRRC Filter

**Receiver**
- Signal Recovery
- SRRC Filter

**Graphs:**
(a) Transmitted SRRC filtered signal
(b) Received SRRC filtered signal
Samples -> Symbol

Modem controls:
8 Samples = 1 Symbol
4 Samples = 1 Symbol
2 Samples = 1 Symbol

QAM64: 1 Symbol = 16 bits out
QAM16: 1 Symbol = 8 bit out
QAM4: 1 Symbol = 4 bits out
Error Correction Coding

- Shannon’s channel capacity theorem sets an absolute limit on the best performance in a band-limited channel.
- Additional bits can be added to a symbol to give it redundancy.
- This redundancy can decrease the probability of error of the system in exchange for reducing the information rate through the system.
- Additional gain can be found if the demodulator includes a certainty metric along with the data decision (soft decision).
- Optimally, the modulated waveform will contain redundancy as well which can also be extracted – e.g., MSK, CPM.

- Raw bits/second (including overhead) vs payload bits/second (excluding overhead)
Thanks
Conclusion

- Mathematics (numbers, units and equations) serves as a universal language through which scientists and engineers from around the world can communicate.

- It only works when we are all clear (use units, use significant figures, use adjectives) in our work.