High Resolution Digital Pen System Using Airborne Ultrasound

Nathan Altman, Qualcomm Inc
Agenda

• Qualcomm intro
• Digital pen overview
  – User experience
  – Key advantages of QC’s solution
• System architecture
• Transmitted signals properties
• Receiver architecture
• Examples of unique problems in airborne ultrasound
• Summary
• Q & A
Born Mobile™

- 27+ years of driving the evolution of wireless communications
- Making wireless more personal, affordable and accessible
- World’s largest fabless semiconductor company
- S&P 100/ S&P 500/ Fortune 500
- #1 in wireless semiconductors
- #1 CPU, GPU, DSP, Power performance

Qualcomm Israel
- Established Haifa in 1993 as Qualcomm’s first R&D center outside the U.S.
- ~500 employees across 3 sites
- Local Qualcomm Ventures activity
- Active in local M&A
- Eco-system support with Israeli innovators

The 4th Annual International TCE Conference
Digital Acoustic Positioning by Epos

- 2003: Company founded
- 2007: First products shipments
- 2009: Cooperation with Qualcomm
- 2011: Wacom Inkling launch
- 2012: Assets acquired by Qualcomm
Mobile Device Digital Pen Market

Digital Pens Becoming Prevalent

ASUS VivoTab
Samsung ATIV Smart PC
Sony Xperia Z Ultra
Microsoft Surface Pro

Samsung Galaxy Note 10.1
Samsung Galaxy Note III
Sony Vaio Duo 11
HP ElitePad 900
General/Standard Digital Pen Use Cases

- **Scribble**: draw, write, highlight, annotate
- **Screen Snapshot**
- **Note Taking**
- **E-Book Editing**
- **Digital Signature**
- **Painting / Drawing**
Consumers ready to write on mobile devices*

* Survey conducted by Samsung in 2011
Ultrasound Positioning technology

- **Software Receiver Solution:** utilizes host’s resources – microphones, CODEC and application processor
  - minimal footprint, **low BOM**
- **Digital Acoustics Technology:**
  - Calculation based on ToA & DTOA
  - Correlation of expected and received signals
  - Utilizing carrier and base-band information
  - Continuous transmission of a band limited series
  - Orthogonal series (multi-access architecture)
A movie is worth a thousand words...

Link: ..\Users\naltman\Videos\Snapdragon_Digital_Pen_demo_Big.mp4
New and Unique Pen Use Cases

**Write-Beside**
A second screen experience

**3/D Input**
True Z-axis input up to 30cm

**Hi-Res Pen Angle**
Angle data enriches input

**Smart Stand Mode**
Enable input on surface

**Simultaneous pen & touch**
Control off-screen input

**Pen pressure sensitivity**
Supporting 2048 levels
Transmitted Signals Properties

- Signals are generated from “Gaussian Series” equations
  - \( p=71, M=1 \) for lower transducer
  - \( p=71, M=82 \) for upper transducer

- The frequency bins are distributed in pseudo random manner across 25-88 KHz spectrum
  - Frequency bins of the 2 transducers are mutually exclusive, keeping orthogonality in the frequency domain

- Other pens use different “M’s”, allowing multi-access architecture

\[
S_n = e^{-\frac{2\pi i M n^2}{p}}
\]

\( 0 \leq n < p-1 \)
Digital Ultrasound ToA Estimation

- Positioning done by Time of Arrival (TOA) estimation, using correlation of expected and received signals.
- Usage of carrier and base-band information:
  - Enhanced accuracy
  - Multipath immunity
- Signal bandwidth (“B”) and carrier frequency (“f_\text{c}”) are in the same order, allowing better ToA estimation without ambiguity problems.

\[
\text{Var}(\text{ToA}) = \frac{3}{\text{SNR} \cdot \pi^2 \cdot (B^2 + 12 \cdot f_\text{c}^2)}
\]
Receiver Architecture

(*) Algorithms dealing with unique problems related to airborne ultrasound
Unique Problems in Airborne Ultrasound

Multipath

- Multipath distance of less than $\lambda_c$ (=6mm), uncontrolled user behavior
  - As the multipath signal approaches the LoS signal, it becomes difficult to resolve the LoS position

- Multipath amplitude can be higher than the LoS signal, especially at high tilts
  - Solid objects reflect 100% of the energy

- Multipath energy is prominent for “long” time (10’s of milli-seconds): high ISI

- Multipath effects the LoS signal “far” from main lobe

- Users may block mics partially or entirely
  - Partial and intermittent mic blocking is more difficult to detect
Unique Problems in Airborne Ultrasound

Speed of Sound Variations

- Distance is proportional to ToA by a factor of $C_{\text{air}}$ or “Speed of Sound” (SoS): $\text{Distance} = C_{\text{air}} \times \text{ToA}$

- SoS is highly dependent on atmospheric conditions, mainly on temperature
  - Other factors are air fluctuations, wind, turbulences, pressure, humidity etc…
  - In “standard office environment”, SoS changes in mHz rate, with an amplitude of ~1-2°C

- Mismatch in SoS has major impact on distance calculation:
  - Assuming $T=24^\circ$, ToA=290μSec: Distance=100.209mm
  - Assuming $T=25^\circ$, ToA=290μSec: Distance=100.377mm

- Screens of mobile devices cool and heat dynamically, with temperature gradients across working area

$$c_{\text{air}} = 331.3 \frac{m}{s} \sqrt{1 + \frac{\theta^\circ C}{273.15^\circ C}}$$
Unique Problems in Airborne Ultrasound

Speed of Sound Variations - Solution

- Use the information of the over-determined system to estimate SoS, by minimizing the error function $g(\Theta)$
- Filtering calculated $C_{\text{air}}$, tilts, according to properties of SDF’s
- Triangulation equations:

$$
-b_{jk} + \frac{1}{C_{\text{air}}} \sqrt{(x + h_k J_x - m_j^x)^2 + (y + h_k J_y - m_j^y)^2 + (z + h_k J_z - m_j^z)^2 - d_{jk}} = 0
$$

$j = 1 \ldots N_{\text{mics}}, \quad k = 1 \ldots N_{\text{tx}}$

$$
g(\theta) = g(x, y, z, J_x, J_y, J_z, b_{jk}, C_{\text{air}}) = \sum_{j,k} e_{jk}^2
$$

$m_j$: mic positions
$b_{jk}$: calibration
$h_k$: transducers heights
$d_{jk}$: measurements
$x, y, z$: pen position (unknown)
$J$: pen tilts (unknown)
$C_{\text{air}}$: SoS (unknown)
GDOP & Synchronization

The motivation behind time base recovery

- GDOP (Geometrical Dilution of Precision) analysis:
  - GDOP is a term used in GPS to specify the additional multiplicative effect of GPS satellite geometry on GPS precision, showing how errors in the measurement will effect the final position estimation.
  - High GDOP indicates that the solution is sensitive to errors
  - $GDOP = \frac{\Delta Output Location}{\Delta Measured Data}$

- Synchronizing the receiver allows using triangulation equations, which have significantly lower GDOP than multilateration equations.

- Transmitter and receiver are not synchronized, thus require continuous timing recovery
Time Base Recovery

Time base recovery from ultrasound signal

- Linear fitting of the estimated signal emission time
- “Circular” dependency in SoS estimation
- GDOP deteriorates quickly when outside the mic array area
  - Practically usable only on the “screen” area

Directly Above: Multilateration (DToA) → Emission time recovery → Time base recovery

Diagram: Time dilution of precision current least squares

- High GDOP shows noisy timing

Graph: Raw time base vs. Frame count

The 4th Annual International TCE Conference
Time Base Recovery

Time base recovery from RF signal

- RF (magnetic) signal arrives instantaneously (speed of light)
- Filtering needed due to noisy magnetic spectrum
  - Coherent noise
  - Signal is integrated ("summing") to gain SNR
- Linear fitting performed after outliers removal

\[
Var(ToA) = \frac{3}{SNR \cdot \pi^2 \cdot (B^2 + 12 \cdot f_c^2)}
\]
Summary

- Digital Pens Becoming Prevalent
- Qualcomm provides unique user experience
- Airborne ultrasound has unique and interesting problems in signal processing
- Contact us for further details:
  Nathan Altman
  naltman@qti.qualcomm.com
  054-6656057