ReMix

In-Body Backscatter Communication and Localization
Motivation

• Rice-size microchip capsules can be deployed in people or animals for identification, tracking and sensing.
• Current capsule’s use half of their energy on RF transmission.
• Currently unable to localize the capsule.
• Backscatter is one of the most power-efficient communication technologies and can be used for localization.
Attenuation Increase Exponentially

- **Surface Interference** – A large portion of the signal is reflected as soon as it hits a human’s surface due to the large difference in electrical properties.

- **Signal Deflection** – RF signals propagate slower in the human body and doesn’t travel in a straight line.
Attenuation Increase Exponentially

- Attenuation increases exponentially in-body because of the electrical permittivity and relative magnetic permeability of biomaterial (e.g. muscle, fat, skin).
Attenuation Increase Exponentially

- Wireless channel is given by $h(f, d)$ where $A$ is the attenuation.
- Speed of light biomaterial is affected by electrical permittivity.
- To understand the impact of the electrical permittivity we will rewrite it in terms of $\alpha$ and $\beta$.
- The higher the value of $\beta$ the higher the loss.

$$h(f, d) = \frac{A}{d} e^{-j2\pi f \frac{d}{c}}$$

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

$$h_M(f, d) = \frac{A}{d} e^{-j2\pi f \frac{d\sqrt{\varepsilon_r}}{c}}$$

$$\sqrt{\varepsilon_r} = \alpha - \beta j$$

$$\frac{A}{d} e^{-j2\pi f \frac{d\alpha}{c}} e^{-2\pi f \frac{d\beta}{c}}$$
Wavelength Shrinks

- The phase changes $\alpha$ times faster in biomaterial than in air because the wavelength is $\alpha$ times smaller.
- Useful for RF-based localization because it increases sensitivity and allows for measuring smaller distances.
Signal Reflection

• The electric permittivity affects what happens at the interface between two materials.

• A large portion of the power is reflected before it reaches the implant.

• Signal needs to travel twice for backscatter.

\[
\frac{P_r}{P_t} = \left| \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \right|^2
\]
Signal Refraction

• When RF signals traverses the between two materials, they experience a change in direction.

• The air-skin interface shows that refraction angle is always near zero.

• Since EM waves paths are reversible, the RF signal that exits the body must arrive almost perpendicular to the body surface.

\[ \text{Re} (\sqrt{\varepsilon_r}) \sin \theta_i = \text{Re} (\sqrt{\varepsilon_r}) \sin \theta_t \]
Antennas Become Less Efficient

• The electrical permittivity of a material effects antennas efficiency depending on antenna design.
• The antenna efficiency in-body is reduced by 10-20 dB.
• The effective area of radiation of an in-body antenna is much smaller than the skin area.
Dealing with Body Reflection

• If reflection from skin is sufficiently different frequency, then it can be filtered out.

• State-of-the-art backscatter system use a battery powered backscatter clock.

• Remix achieves a similar goal by using a diode connected to an antenna.

• Receives signals at two frequencies and backscatter combinations of these frequencies.
ReMix’s Localization Algorithm

• Estimate the distance traveled by the signal as if it were traveling in air.

• Phase equation for $f_1 + f_2$

• Similar equation for $2f_1 - f_2$

• We can use another receiver $r'$ to get two additional equations that are functions of $d_1$, $d_2$, $d_r$, and $d_r'$

\[
\phi_i = -\frac{2\pi}{c} (f_1 d_1 + f_2 d_2 + (f_1 + f_2) d_r) \mod 2\pi
\]

\[
\psi_i = -\frac{2\pi}{c} (2f_1 d_1 - f_2 d_2 + (2f_1 - f_2) d_r) \mod 2\pi
\]
ReMix’s Localization Algorithm

• Propagation in each layer is linear but across layers it can change directions.
• Known: $X_i$, $\epsilon_{rf}$, and $\epsilon_{rm}$
• Goal: Estimate $(x, y)$, $l_m$, and $l_f$
ReMix’s Localization Algorithm

- Spline Comprised of 3 Segments
  - In-air $d_a^i$
  - In-fat $d_f^i$
  - In-muscle $d_m^i$

- Angle of Incidence
  - In-air $\theta_a^i$
  - In-fat $\theta_f^i$
  - In-muscle $\theta_f^i$

- Refraction Constraints

- Geometric Constraints

\[
Re(\sqrt{\varepsilon_{ra}}) \sin \theta_a^i = Re(\sqrt{\varepsilon_{rf}}) \sin \theta_f^i \\
Re(\sqrt{\varepsilon_{rm}}) \sin \theta_m^i = Re(\sqrt{\varepsilon_{rf}}) \sin \theta_f^i \\
\]

\[
d_a^i = \frac{l_a}{\cos \theta_a^i}, d_f^i = \frac{l_f}{\cos \theta_f^i}, d_m^i = \frac{l_m}{\cos \theta_m^i} \\
d_a^i \sin \theta_a^i + d_f^i \sin \theta_f^i + d_m^i \sin \theta_m^i = (X_i - X)_1
\]
ReMix’s Localization Algorithm

• We can denote the length of the segments of the spline corresponding to antenna $i$ in air, fat and muscle.

• Combining distance measurements from multiple antennas we get our optimization function.

\[
\hat{d}_a^i(X, l_m, l_f), \hat{d}_f^i(X, l_m, l_f), \hat{d}_m^i(X, l_m, l_f)
\]

\[
\hat{X}, \hat{l}_m, \hat{l}_f = \arg \min_{X, l_m, l_f} \sum_{i=1}^{N} ||\hat{d}_a^i(.) + \alpha_f \hat{d}_f^i(.) + \alpha_m \hat{d}_m^i(.) - d_i||^2
\]
Empirical Results - Microbenchmarks

- Tested in-air and had variations in power in different frequency bands.
Empirical Results – Interchange Layers

• The order of layers can be changed without impacting the phase of the signal.

<table>
<thead>
<tr>
<th>Config</th>
<th>Layer Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Skin, Fat, Muscle, Fat, Muscle, Muscle, Bone</td>
</tr>
<tr>
<td>2</td>
<td>Muscle, Fat, Muscle, Fat, Skin, Muscle, Bone</td>
</tr>
<tr>
<td>3</td>
<td>Skin, Fat, Muscle, Fat, Muscle, Bone, Muscle</td>
</tr>
<tr>
<td>4</td>
<td>Muscle, Fat, Muscle, Fat, Skin, Bone, Muscle</td>
</tr>
<tr>
<td>5</td>
<td>Bone, Muscle, Skin, Fat, Muscle, Fat, Muscle</td>
</tr>
</tbody>
</table>
Empirical Results – Lack of in-body Multipath

- ReMix’s backscatter device was placed inside a box of chicken meat.
- Phase has a linear relationship with distance.
- Indicates in-body multipath for ReMix is mild to non-existent.
Backscatter Communication

- Achieved average SNR of 15 dB for 1 Mhz frequency band when the tissue depth is up to 8 cm.
- This SNR can be improved by combining multiple antennas.
In-Body Localization

• Variance: For typical variance in human tissue properties, ReMix’s localization error continues to be < 2 cm.
In-Body Localization

• ReMix can achieve high localization accuracy of 1.3 cm in human phantom and 1.4 cm in chicken
Conclusion

• ReMix achieves the first deep tissue backscatter communication.
• Uses circuit non-linearities to shift the frequency of the backscatter signal to avoid interference from surface reflections.
• Presents a time-of-flight localization algorithm that accounts for in-body signal refraction.