ReMix

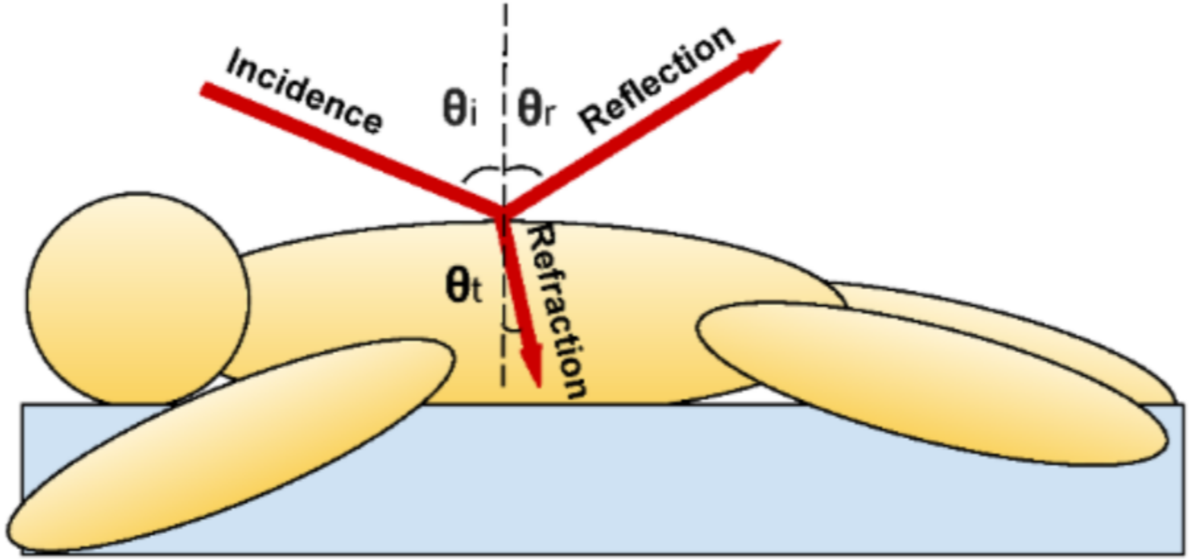
In-Body Backscatter Communication and Localization

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.

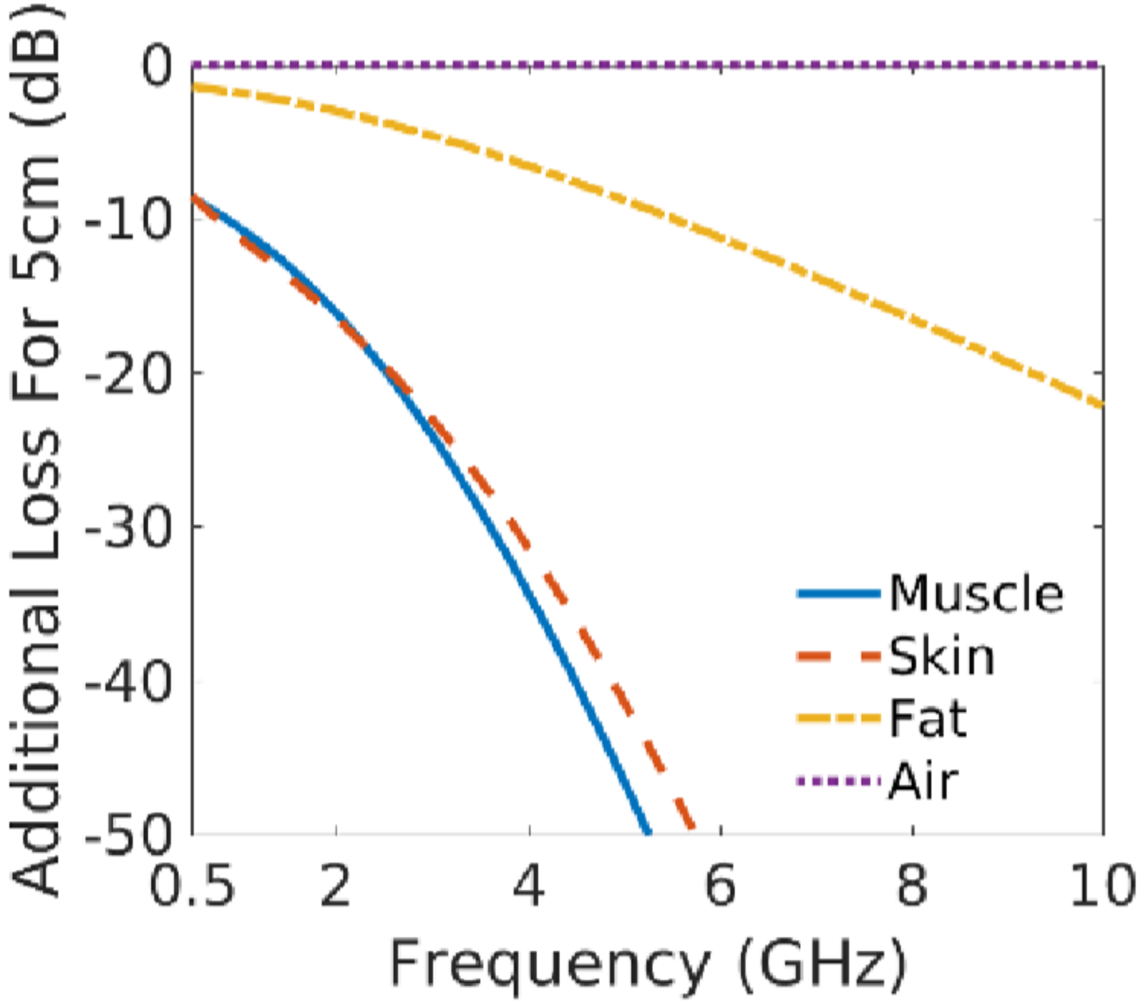
Attenuation Increase Exponentially

- **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 α and β.
- The higher the value of β the higher the loss.

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

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

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

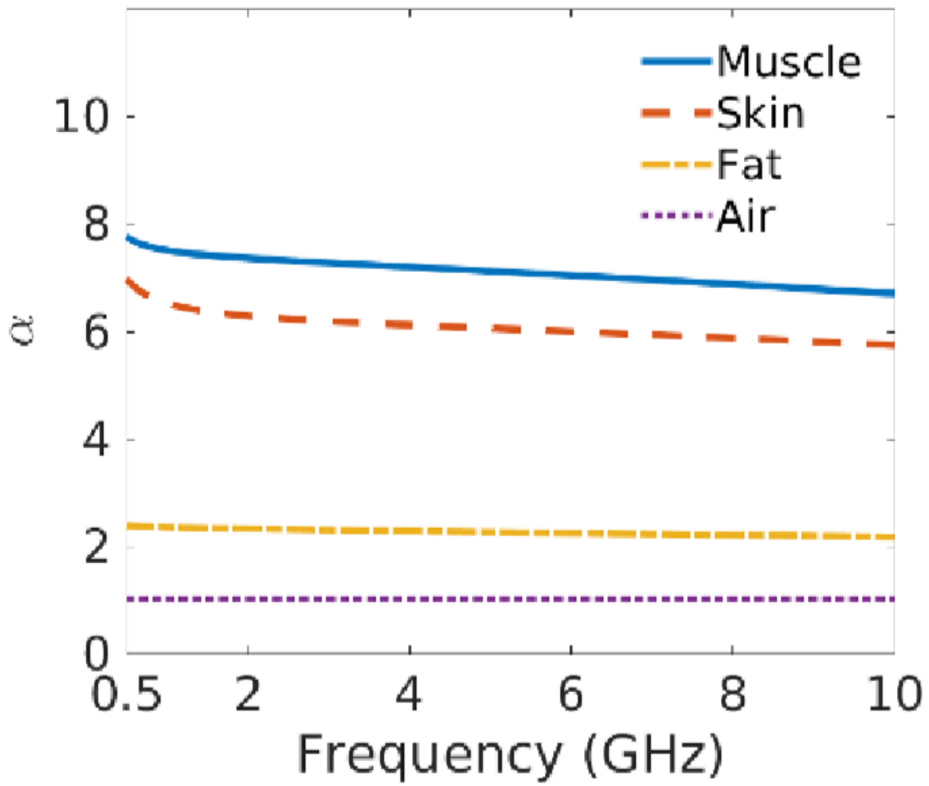
$$\sqrt{\epsilon_r} = \alpha - \beta j$$

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

Wavelength Shrinks

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

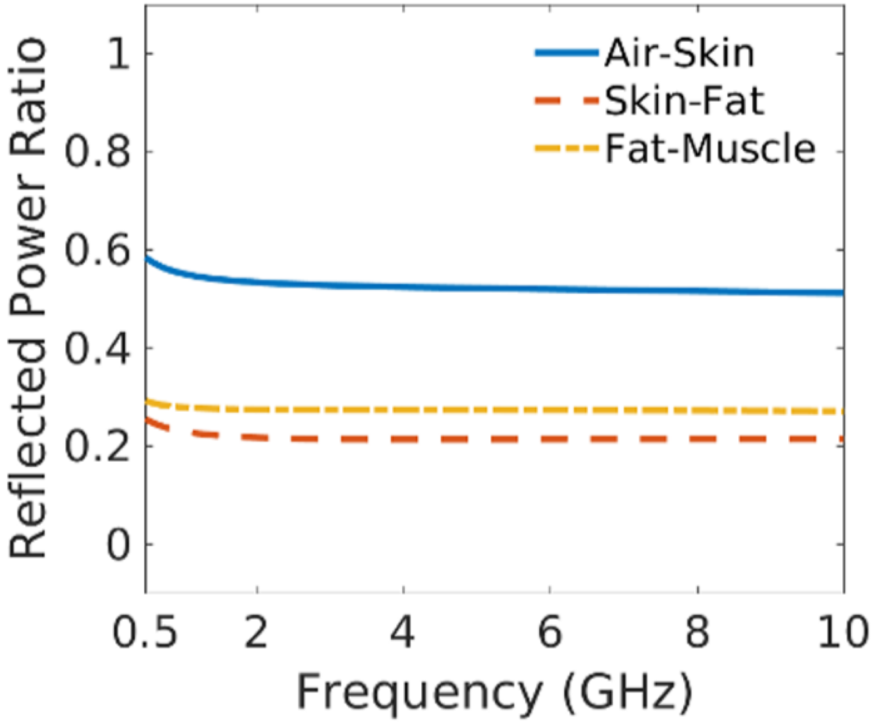
$$\frac{A}{d} e^{-j2\pi f \frac{d\alpha}{c}} e^{-2\pi f \frac{d\beta}{c}}$$



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.

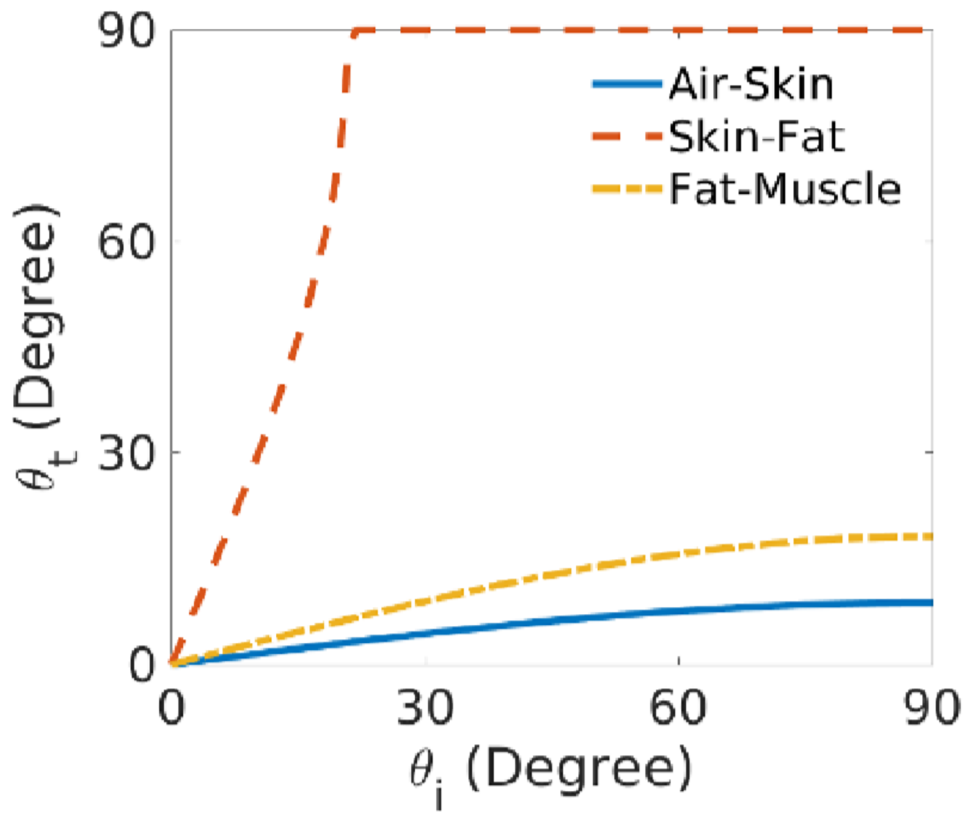
$$\frac{P_r}{P_t} = \left| \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} \right|^2$$



Signal Refraction

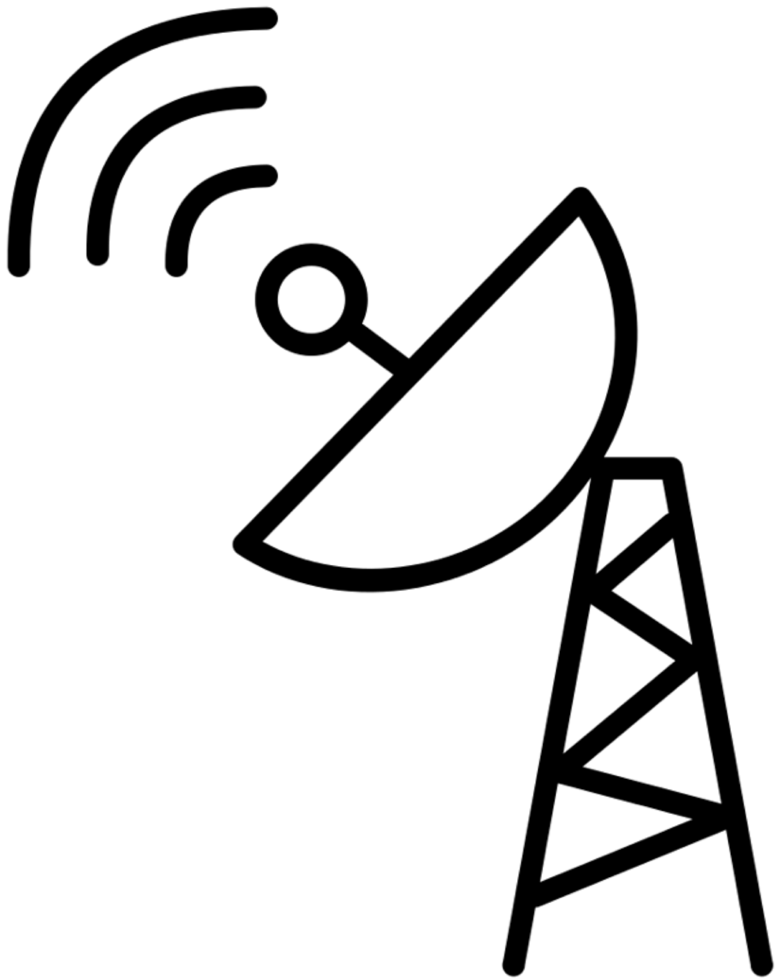
- When RF signals traverses the between two materials, they experience a change in direction.
- The air-skin interface shows that refraction angle is always near zero.
- Since EM waves paths are reversible, the RF signal that exits the body must arrive almost perpendicular to the body surface.

$$Re(\sqrt{\epsilon_{r1}})\sin\theta_i = Re(\sqrt{\epsilon_{r2}})\sin\theta_t$$



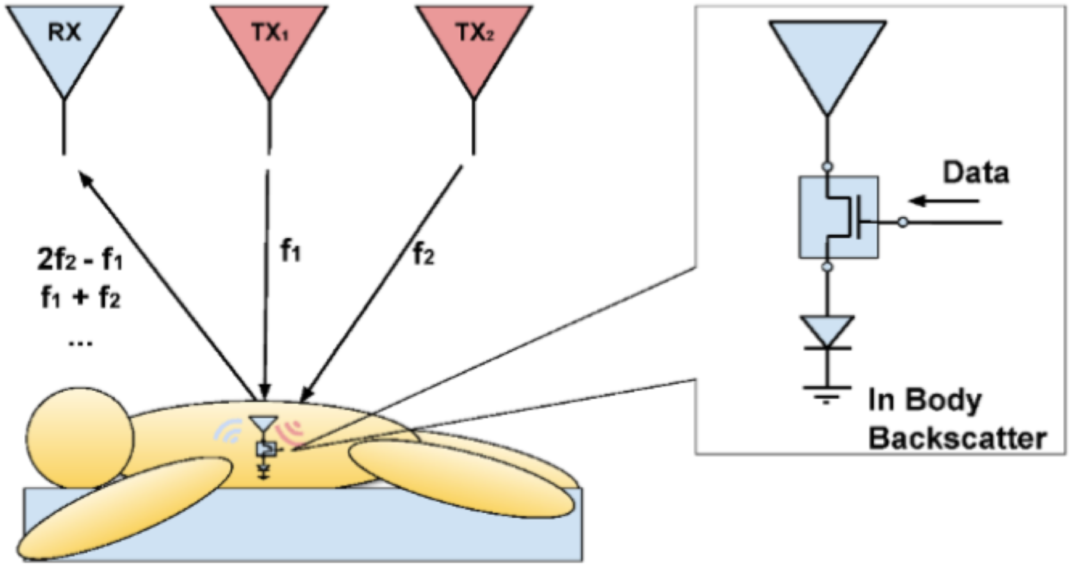
Antennas Become Less Efficient

- 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

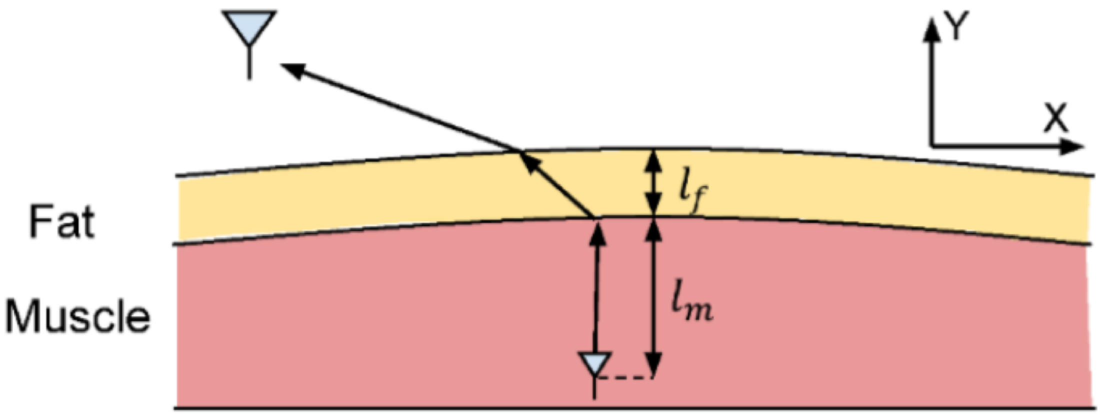
- Estimate the distance traveled by the signal as if it were traveling in air.
- Phase equation for f1 + f2
- Similar equation for 2f1 – f2
- We can use another receiver r’ to get two additional equations that are functions of d1, d2, dr, and dr’

$$\phi_i = -\frac{2\pi}{c}(f_1 d_1 + f_2 d_2 + (f_1 + f_2) d_r) \bmod 2\pi$$

$$\psi_i = -\frac{2\pi}{c}(2f_1 d_1 - f_2 d_2 + (2f_1 - f_2) d_r) \quad \bmod 2\pi$$

ReMix's Localization Algorithm

- Propagation in each layer is linear but across layers it can change directions.
- Known: X_i, ϵ_{rf}, and ϵ_{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 θ_a^i
  - In-fat θ_f^i
  - In-muscle θ_f^i
- Refraction Constraints
- Geometric Constraints

$$Re(\sqrt{\epsilon_{ra}}) \sin\theta_a^i = Re(\sqrt{\epsilon_{rf}}) \sin\theta_f^i$$
$$Re(\sqrt{\epsilon_{rm}}) \sin\theta_m^i = Re(\sqrt{\epsilon_{rf}}) \sin\theta_f^i$$

$$d_a^i = \frac{l_a}{\cos\theta_a^i}, d_f^i = \frac{l_f}{\cos\theta_f^i}, d_m^i = \frac{l_m}{\cos\theta_m^i}$$
$$d_a^i \sin\theta_a^i + d_f^i \sin\theta_f^i + d_m^i \sin\theta_m^i = (X_i - X)_1$$

ReMix's Localization Algorithm

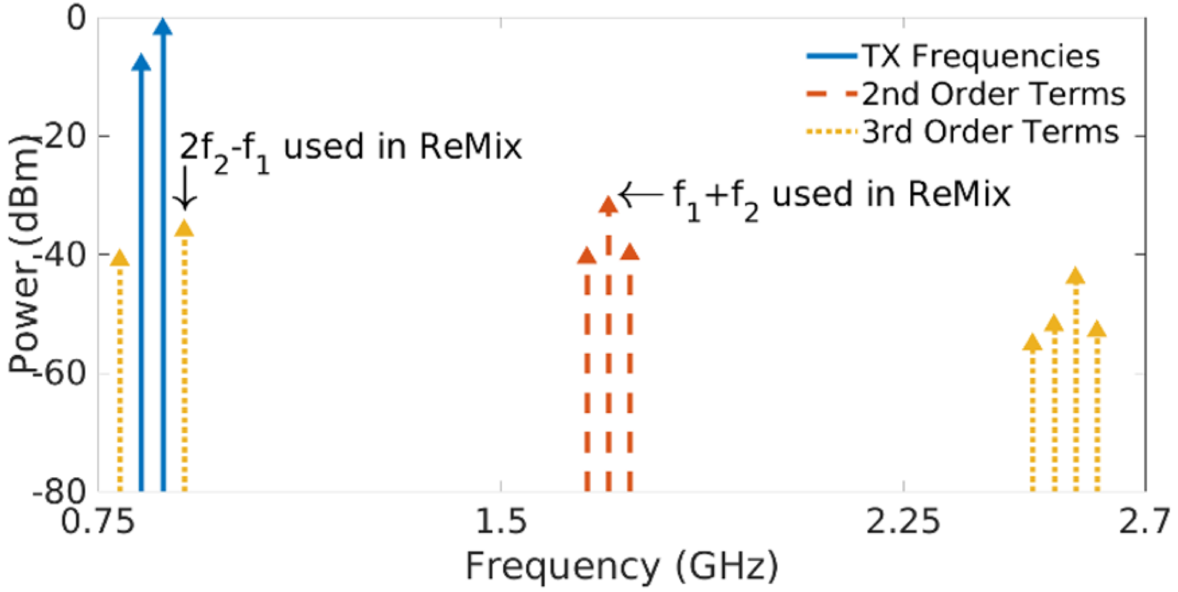
- We can denote the length of the segments of the spline corresponding to antenna i in air, fat and muscle.
- Combining distance measurements from multiple antennas we get our optimization function.

$$d_a^i(X, l_m, l_f), d_f^i(X, l_m, l_f), d_m^i(X, l_m, l_f)$$

$$\hat{X}, \hat{l_m}, \hat{l_f} = \arg\min_{X, l_m, l_f} \sum_{i=1}^{N} ||d_a^i(.) + \alpha_f d_f^i(.) + \alpha_m d_m^i(.) - d_i||^2$$

Empirical Results - Microbenchmarks

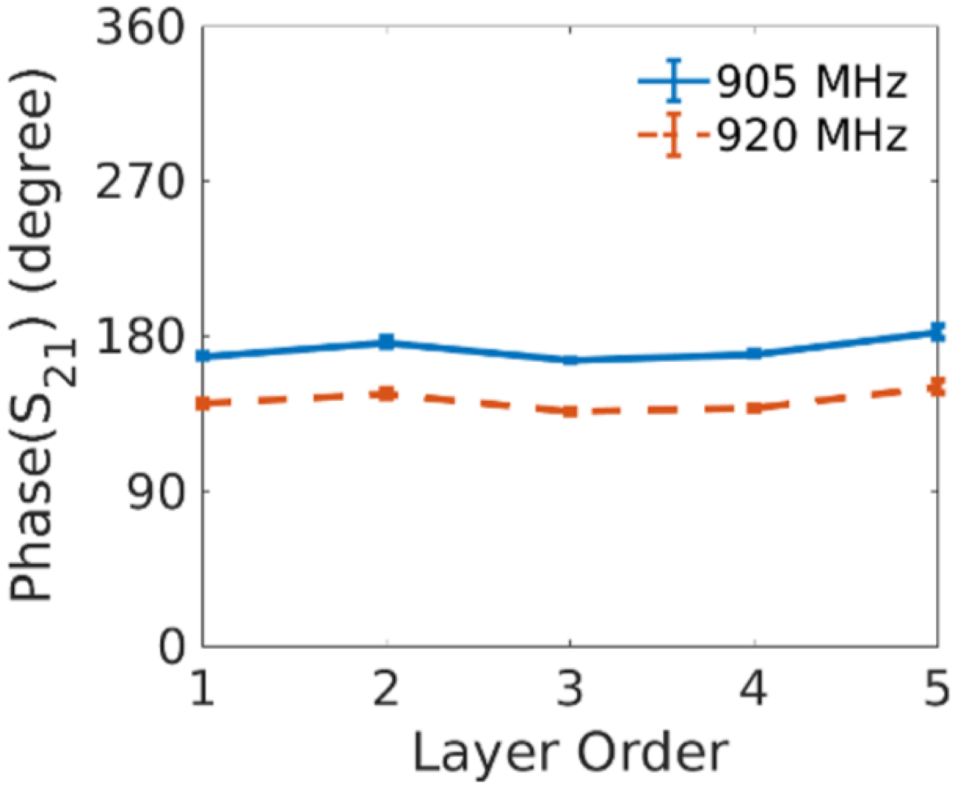
- Tested in-air and had variations in power in different frequency bands.



Empirical Results – Interchange Layers

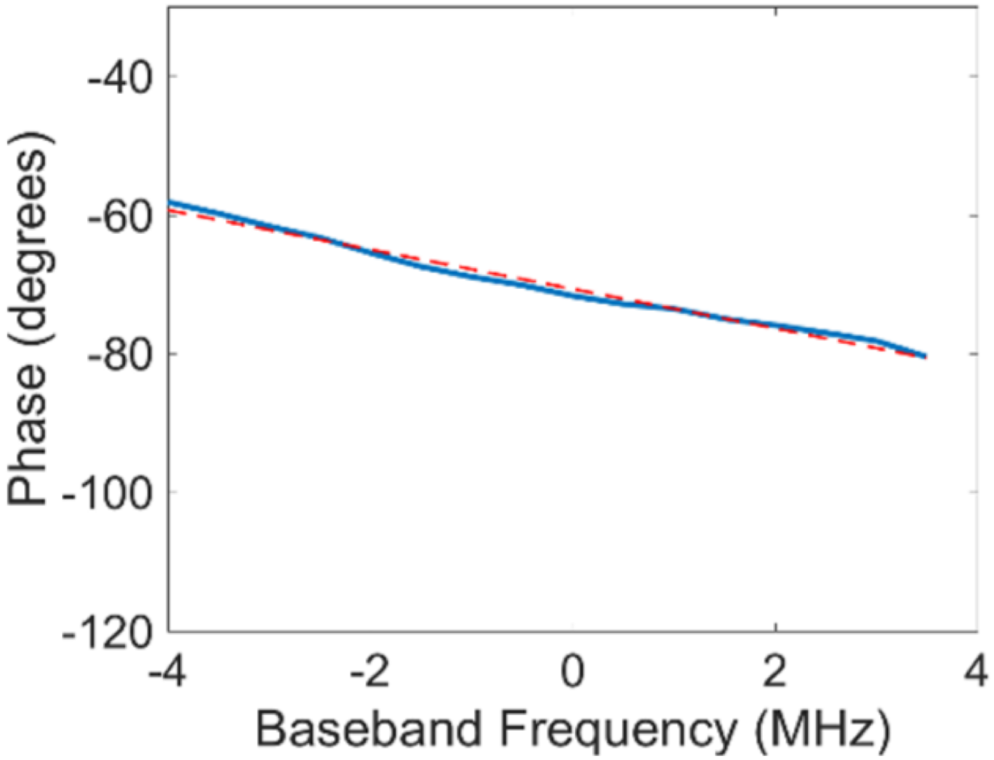
- The order of layers can be changed without impacting the phase of the signal.

Config.	Layer Structure
1	Skin, Fat, Muscle, Fat, Muscle, Muscle, Bone
2	Muscle, Fat, Muscle, Fat, Skin, Muscle, Bone
3	Skin, Fat, Muscle, Fat, Muscle, Bone, Muscle
4	Muscle, Fat, Muscle, Fat, Skin, Bone, Muscle
5	Bone, Muscle, Skin, Fat, Muscle, Fat, Muscle



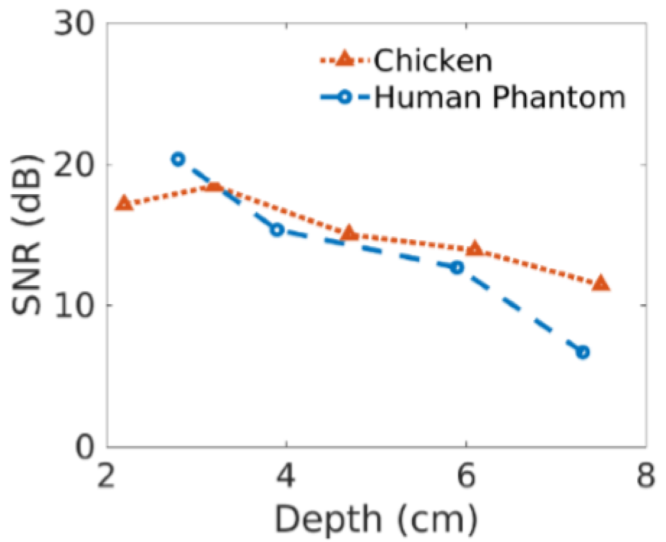
Empirical Results – Lack of in-body Multipath

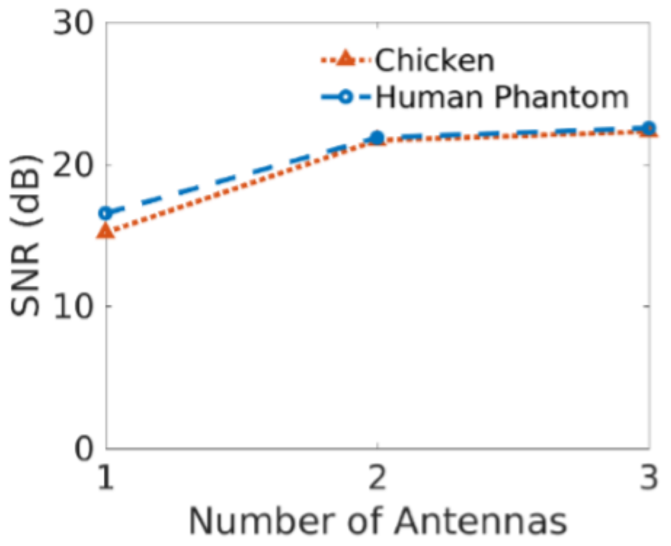
- ReMix's backscatter device was placed inside a box of chicken meat.
- Phase has a linear relationship with distance.
- Indicates in-body multipath for ReMix is mild to non-existent.



Backscatter Communication

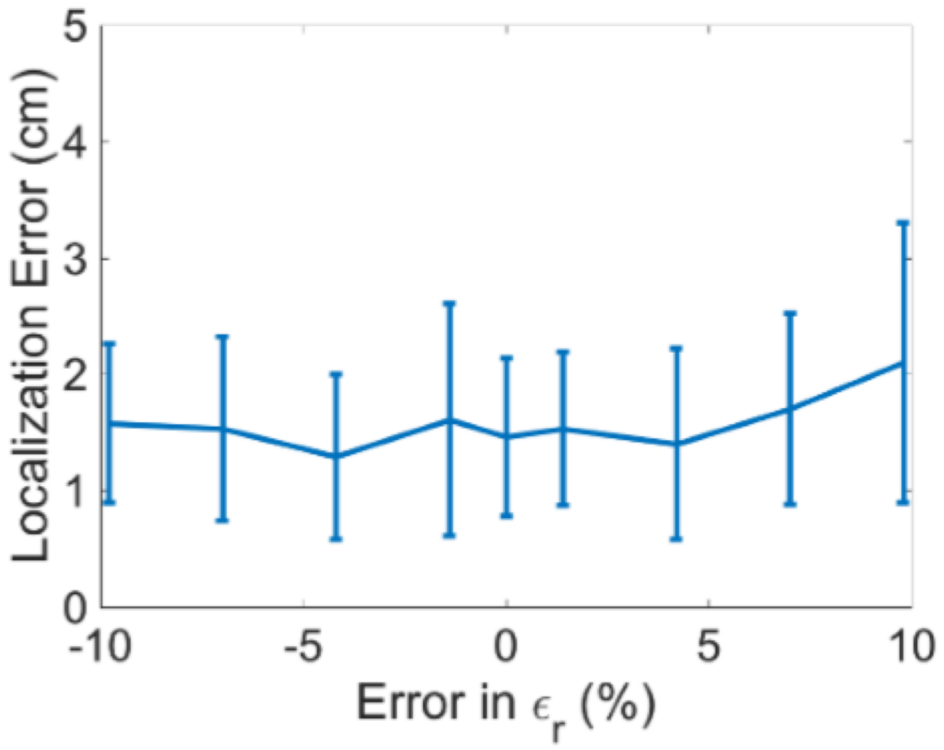
- Achieved average SNR of 15 dB for 1 Mhz frequency band when the tissue depth is up to 8 cm.
- This SNR can be improved by combining multiple antennas.





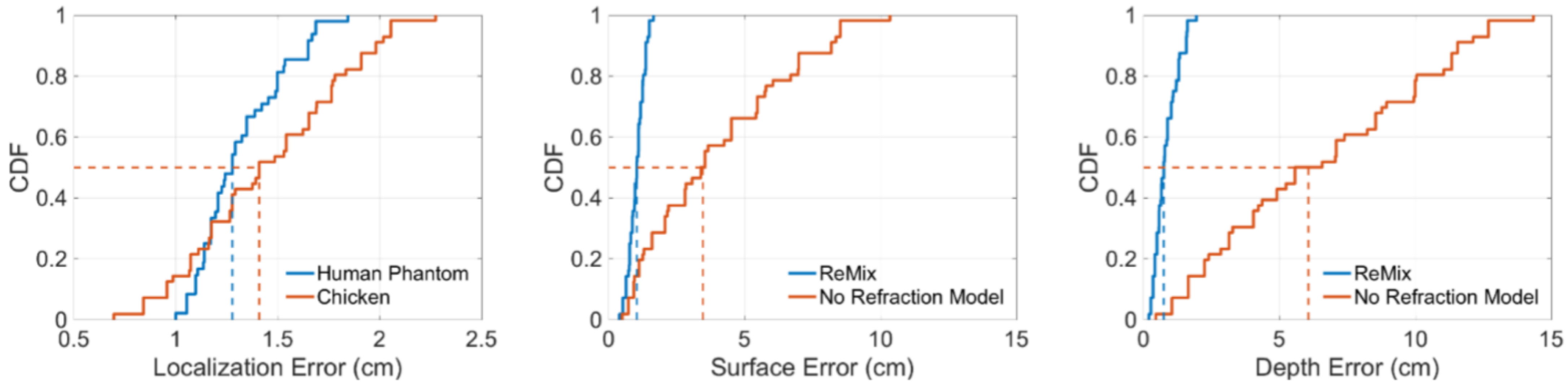
In-Body Localization

- 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.