Theory and Design of Magnetic Induction-Based Wireless Underground Sensor Networks

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WSNs, WUSNs, Applications

- **Wireless Sensor Networks (WSNs):** “more sensing points at low-cost”

- **Wireless Underground Sensor Networks (WUSNs):**
  a) No physical obstruction
  b) Physical protection / concealment
  c) When free-space communication is not an option

* References at the last slide
WUSN applications

Precise irrigation \[4-9\]

Prescribed burn research

Infrastructure monitoring \[5-7, 10\]

Situational Awareness Systems \[3\]
WUSN: low-power PHYsical layer solutions

• Mobile terrestrial data collector
  😊 Feasibility demonstrated[^4]
  😞 Limited to few scenarios[^7]

• Radio wave propagation
  😞 High signal attenuation (e.g., > 30dB/m) [^5-^9]
  😊 Feasibility demonstrated for lateral waves antennas[^9]
  ... but solution fails at high soil moisture content

• Magnetic Induction (MI)

[^4]: Center Pivot experiment, Clay Center, NE (December 2009): 10dBm, 433MHz
[^5-^10]: Challenges
  .. lack of real-world experiment (15..30m)
  .. what frequency range?
  .. soil dielectric model?
  .. practical signal attenuation model?
Mid-range (15..30m) MI-WUSN: frequency range

- Square cross-section, multilayer circular coils, 30cm-diameter
- Medium loam soil 23% clay, 52% silt

Starting from Maxwell’s equations, investigate asymptotic behavior of $H$

$$H^{MI} = \frac{N_{TX} \cdot S_{TX} \cdot I_{TX} \cdot e^{-\alpha r}}{2\pi r^3}$$

- $\gamma$: complex propagation constant
- $\alpha$: attenuation factor
- $N$: number of turns (coil)
- $I$: sinusoidal current (rms)
- $H$: magnitude of the received magnetic field

**Table**

<table>
<thead>
<tr>
<th>Frequency $f$</th>
<th>Water content WC</th>
<th>Distance $r$</th>
<th>Attenuation factor $\alpha$</th>
<th>$e^{-\alpha r}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 KHz</td>
<td>5%</td>
<td>10m</td>
<td>0.00046 Np/m</td>
<td>0.9954</td>
</tr>
<tr>
<td>1 KHz</td>
<td>40%</td>
<td>10m</td>
<td>0.00229 Np/m</td>
<td>0.9774</td>
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<tr>
<td>1 KHz</td>
<td>40%</td>
<td>30m</td>
<td>0.00229 Np/m</td>
<td>0.9336</td>
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<tr>
<td>10 KHz</td>
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<td>10m</td>
<td>0.01539 Np/m</td>
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<tr>
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<td>30m</td>
<td>0.01539 Np/m</td>
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<tr>
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<td>5%</td>
<td>30m</td>
<td>0.01348 Np/m</td>
<td>0.6674</td>
</tr>
<tr>
<td>100 KHz</td>
<td>40%</td>
<td>30m</td>
<td>0.1020 Np/m</td>
<td>0.0469</td>
</tr>
</tbody>
</table>

- For $r=30m$, MI solution is very robust at audio frequencies
- Dynamic frequency selection is feasible

-1 dB
-4 dB
-27 dB
MI-WUSN: sub-MHz soil dielectric model

这个地图

Not available for low frequencies (LF): the single existing one is not accurate

Why?

.. soil + LF: multiple polarization mechanisms
.. soil + LF: measurements errors due to “electrode polarization” (EP)

EP software-corrected: applied to 9 types of soils

• When applied to the received MI signal strength model: overall error smaller than 10%

• Not accurate enough for non-communication purpose: currently being investigated
**MI-WUSN: practical MI signal attenuation model**

😊 **First MI-WUSN** work that does not include “M” (mutual inductance)

- **Input parameters:** frequency, class of soil, water content, and circuitry aspects (diameter of coil, #turns, etc.)

- The proposed empirical soil dielectric model allowed us to **group 9 types of soil into 3 classes** typically, generic soil models follow this pattern.
MI-WUSN: MI signal attenuation model validation

- Empirical work: 10KHz
- **MI-SOIL** avg error: **-8.9%**; avg error (water >=15%): **5.6%**
- **Scott’s 67** [11] avg error: **-27.5%**; avg error (water >=15%): **-66.5%**
Thank you!!

References:


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