Detection, Identification, Location, and Remote Sensing Using SAW RFID Sensor Tags

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Introduction to Surface Acoustic Wave (SAW) RFID tags

Overview of the NASA JSC Passive Adaptive RFID Sensor EQuipment (PARSEQ) system

PARSEQ simulated performance evaluation

PARSEQ experimental performance evaluation

PARSEQ field test

Future Work
SAW RFID Tags

- RF interrogator signal (ISM Band: 2.40 – 2.48 GHz)
- InterDigital Transducer (IDT) converts RF signal at antenna to acoustic wave
- Piezoelectric substrate propagates acoustic signal
- Reflector spacing determines unique ID
- IDT converts acoustic wave back to RF at antenna
SAW RFID Tags – Advantages

- Completely passive wireless device
- Very rugged
  - Withstands extreme temperatures (~20° K to several hundred
  - Withstands extreme acceleration
  - Operates in vacuum
- Tag can be interrogated with extremely low power
  - Increased interrogation range
  - Reduced danger near pyrotechniques
- Provides remote sensing capability
  - Tag response modulated by tag temperature and tag strain
  - Can be interfaced with other passive sensors (load subset of reflectors with variable impedance device)
High insertion loss and low-power response

Must estimate temperature to read tag ID accurately

Fabrication complexity and cost increase with frequency of operation
Magnitude of normalized tag impulse response at -73° C
Temperature

Computed from estimated scale (compression/dilation) of received waveform

Range

Computed from estimated time delay of received waveform

Estimation

Suboptimal and not robust to tag collision

- Detect individual pulses
- Estimate time of arrival (TOA) for each pulse directly
- Use TOA of first pulse to compute waveform time delay and delay between pulses to compute waveform scale

Optimal and robust to tag collision

- Estimate time scale and time delay of waveform simultaneously using wavelet transform
Tag impulse response magnitude at -73° C (blue) and 21° C (green).
SAW RFID Tags – Temperature Coefficient of Delay (TCD)

Relative Time Delay (wrt 0 deg. C) vs. Temperature (degrees C)

- Graph showing the relationship between relative time delay and temperature.
- The x-axis represents temperature in degrees Celsius, ranging from -50 to 20.
- The y-axis represents the relative time delay, ranging from 0.996 to 1.003.

NASA logo and WiSens4Space 2009 watermark.
Pressure sensors

Stress/strain on crystal causes change in propagation velocity (same as response to temperature)

Incorporation of commercial sensors

Sandia National Laboratory (SNL) concept: FET-loading of SAW IDT with passive sensor driving FET

Passive sensor types under evaluation: accelerometer, acoustic emission

SNL SAW Sensor Concept
**Goals**

Simultaneous detection, identification, location, and remote sensing of multiple objects with passive SAW RFID tags

**Challenges**

For NASA sensor applications, often want many tags within interrogator field-of-view

Ranges > 100 feet are desired for many applications

Primary SAW material in use is very sensitive to temperature

- Good for temperature sensing, but makes other sensors more challenging
- Fully exploit spatial diversity
  - Larger aperture interrogators
  - Adaptive digital beamforming

- Fully exploit time and frequency diversity
  - Wideband processing
  - Wavelet transform
PARSEQ – Software Architecture

Diagram showing the flow of data and logical processes in a software architecture. The diagram includes:
- LabView Script
- Disk Storage
- Beamforming
- Detection and Estimation
- Command Switch
- Display Data
- Fetch Data

Data flow from Display Data to LabView Script, then to Disk Storage, and finally to Beamforming and Detection and Estimation. Logical flow is indicated between these components.
Sample channel frequency response at each receiving antenna

- Stepped CW sweep with network analyzer for each antenna
- Step through receiving antennas with RF switch matrix

Signal preconditioning to remove initial transients in channel impulse response

- Early reflections, transmitter/receiver cross-talk, etc.
- Tag response delay ~1 µsec

Form pre-determined beams in Fourier domain

- Adaptive beam-forming performed at initialization to determine beam coefficients
- Beams can be re-computed as desired

Process beam-formed data to detect/estimate tags

- Current processing sequential with single processor
- Can be fully parallelized
Signal energy distribution in cluttered environment
Example beam data with five tags
Compute sampled 2-D correlation surface (wavelet ambiguity function) for each tag template
  - Scaled tag templates pre-computed
  - Minimal computational burden to compute correlations

Determine maximum correlation peak
  - Nothing above threshold: no tags detected in beam
  - Maximum peak over threshold: corresponding tag detected

Estimate range and temperature for detected tag
  - Nonlinear optimization to maximize correlation value in vicinity of detected correlation peak
  - Optimization represents nearly all of computational burden: O(N^3)

Successive interference cancellation (SIC)
  - Project residual signal on detected, scaled template
  - Remove projection to form new residual
Correlation surface with wavelet matched to single tag response
Correlation surface with wavelet not matched to single tag response
Correlation surface with strongest response prior to SIC processing for two-tag superposition signal
Correlation surface with strongest response after SIC processing for two-tag superposition signal
Correlation surface with second strongest response prior to SIC processing for two-tag superposition signal
Correlation surface with second strongest response after SIC processing for two-tag superposition signal
40-bit SAW Tag
Tag IDs selected at random
11 Total tags in simulation

Simulations based on measured tag responses with simulated additive white Gaussian noise
Multiple SNRs
Multiple levels of tag interference

Composite signals formed by summing scaled and shifted tag responses
All tags at different ranges and temperatures
All tags with same energy (worst case overall)

Simulation metrics
Detection probability
False alarm probability
Mean-squared temperature and range error
Simulated Performance – Example Waveforms

Single Tag – No AWGN

Single Tag – 25 dB

Single Tag – 20 dB

Single Tag – 15 dB
Simulated Performance – Probability of Detection

Number of Tags

Pd

15 dB
16 dB
17 dB
18 dB
19 dB
20 dB
21 dB
22 dB
23 dB
24 dB
25 dB
26 dB
27 dB
28 dB
29 dB
30 dB
Simulated Performance – Probability of False Alarm

[Graph showing the probability of false alarm (Pfa) versus the number of tags for different signal-to-noise ratios (SNR) in decibels (dB): 30 dB, 29 dB, 28 dB, 27 dB, 26 dB, 25 dB, 24 dB, 23 dB, 22 dB, 21 dB, 20 dB, 19 dB, 18 dB, 17 dB, 16 dB, 15 dB. The graph indicates how the probability of false alarm increases with the number of tags for each SNR level.]
Simulated Performance – Temperature Estimation

The graph illustrates the Mean Squared Error (MSE) in degrees Celsius squared as a function of the number of tags for different signal-to-noise ratios (SNR) in milliwatts (dB). Each curve represents a different SNR level, with 30 dB being the highest and 15 dB the lowest. The MSE increases as the number of tags increases, indicating a decrease in temperature estimation accuracy.
Simulated Performance – Temperature Estimation

MSE (degrees C squared) vs. SNR

- Simulation (blue line)
- C-R Lower Bound (green line)

The graph shows the relationship between Mean Squared Error (MSE) and Signal-to-Noise Ratio (SNR) for simulated temperature estimation. The C-R Lower Bound is indicated by the green line, which serves as a benchmark for the performance of the simulation, represented by the blue line.
Simulated Performance – Range Estimation

MSE (meters squared)

Number of Tags

30 dB
29 dB
28 dB
27 dB
26 dB
25 dB
24 dB
23 dB
22 dB
21 dB
20 dB
19 dB
18 dB
17 dB
16 dB
15 dB
Simulated Performance – Range Estimation

![Graph showing simulated and C-R lower bound for MSE vs SNR](image_url)
Connectorized tag placed in thermal chamber

- Cable to external patch antenna
- Chamber cycled from -72°C to 20°C and back

System configuration

- 8-element Tx antenna array
- 72-element Rx antenna array
- 10 mW transmit power
- ~3 m cable run and ~2 m antenna range
Experimental Performance – Temperature Estimation @ 4.5° C/min
Experimental Performance – Temperature Estimation @ 6° C/min
Experimental Performance – Temperature Estimation @ 11° C/min
Monitor temperature of experimental LOX tank wirelessly

5 tags placed on exterior of tank

Tags placed at same level as wired internal temperature sensors

System configuration

8-element Tx antenna
64-element Rx antenna
~19 ft. baseline range
~25 ft. tag range
Azimuth: tag boresight
Elevation: ~40° off tag bore-sight
Garvey Test – System Orientation

Garvey Spacecraft
Experimental P-9 Rocket

Highly Sophisticated
Mobile Lab
Garvey Test – Tag Placement

SAW RFID Sensor

Rocket Body

Approximate Fill Level

LOX Tank

Tag 5

Tag 4

Tag 3

Tag 2

Tag 1
Garvey Test – Test Results

Temperature (deg C)

Time (sec)

-100
-50
0
50
100
150

-32°
-83°

Truck Moved

Begin Tanking

Tag 2
Tag 3
Tag 4
Tag 5
Future Work

- Integrate calibrated, passive commercial sensors with SAW devices
  
  Primary targets: accelerometers, acoustic emission sensors

- Longer Ranges and higher tag density

- Sample rates significantly higher than current temperature applications: > 10 kHz, compared to 1-3 Hz