Dry and Noncontact EEG Sensors for Mobile Brain-Computer interface.

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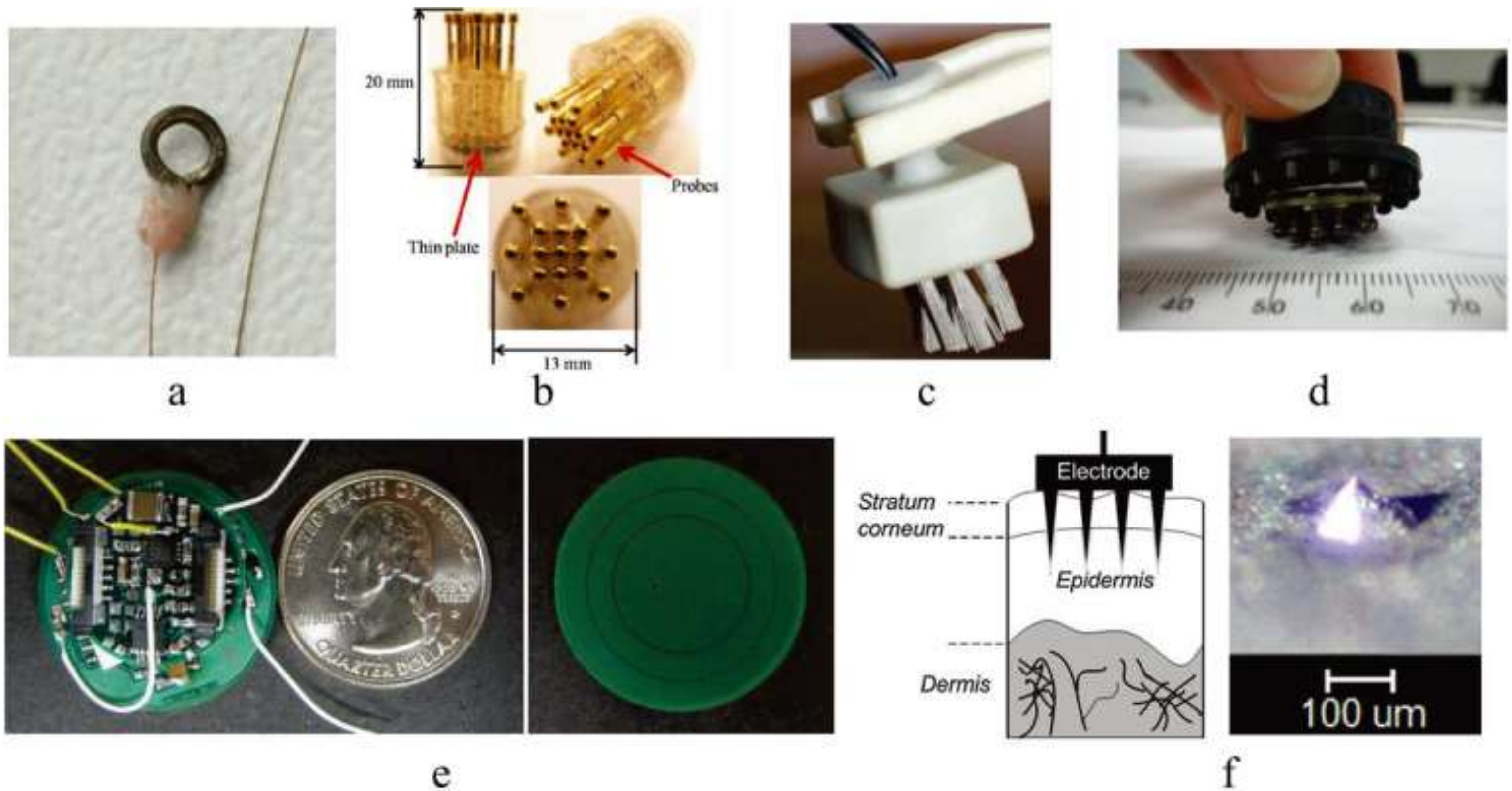
Background

- Various EEG electrodes

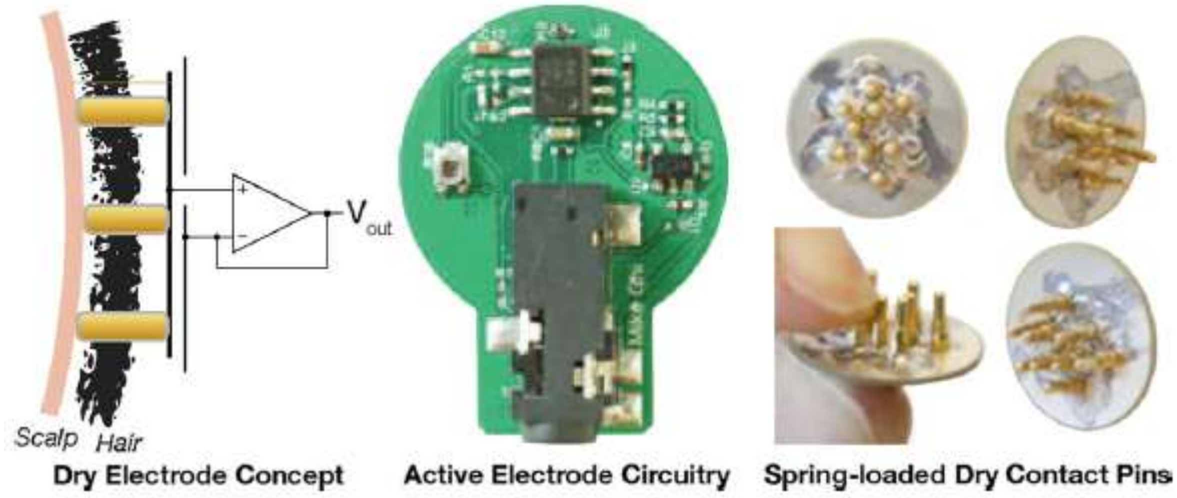


(a) a miniature passive ring electrode (b) a spring-loaded dry electrode (c) a bristle-type dry electrode (d) the Quasar hybrid EEG biosensor (e) a non-contact-type active dry EEG sensor (f) Diagram of a micro-tip electrode and the pyramidal shape of a micro-tip

Introduction

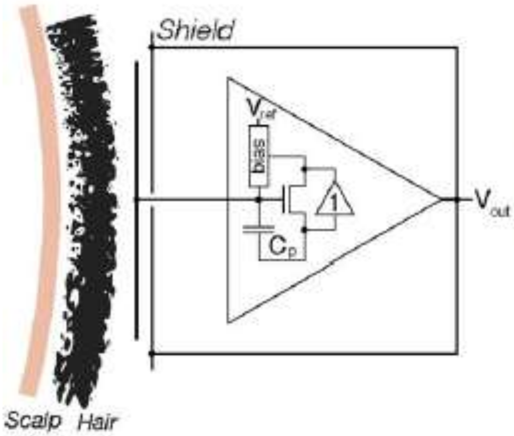
- Introduction
  - In EEG- based BCI systems, conventional BCI systems need extensive preparations such as scalp abrasion, conductive gels for good signal quality. Moreover, multiple wired electrodes are difficult to escape from laboratory scale experiments.
  - To overcome these problems, extensive research produced a variety of dry electrodes.
  - In this paper, they introduced dry and non-contact electrodes and evaluate their performance with SSVEP paradigms.
- Contents
  - Introduction of their dry and non-contact electrodes
  - Offline sensor benchmark with SSVEP paradigm
  - Online decoding test with mobile application

Dry electrodes



- Structure
  - Lower plate : a set of spring-loaded pins, a male snap connector
  - Upper PCB : active electrode circuitry (CMOS-input opamp, LMP7702)
  - Unity gain buffer (gain=1) with shielded cable
  - No discomfort, injury hazard

Non-contact electrodes



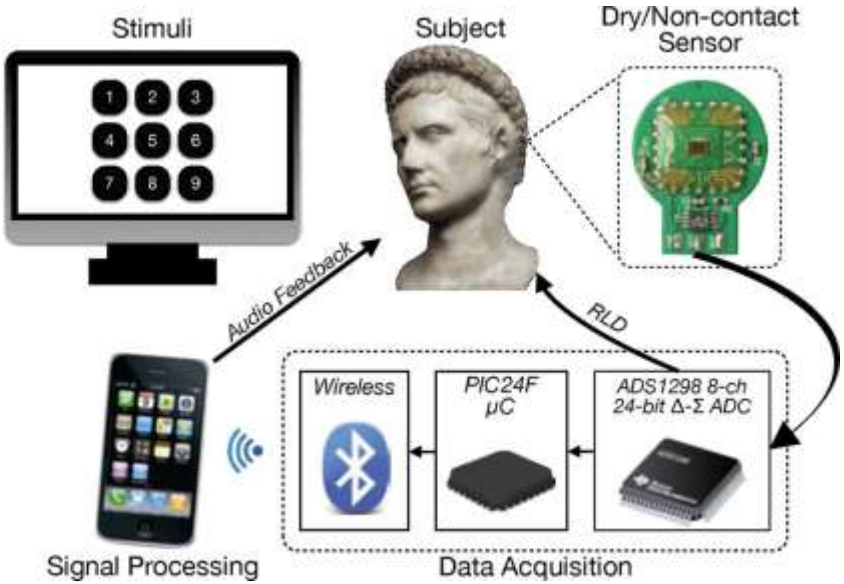
Integrated Non-contact Electrode Concept

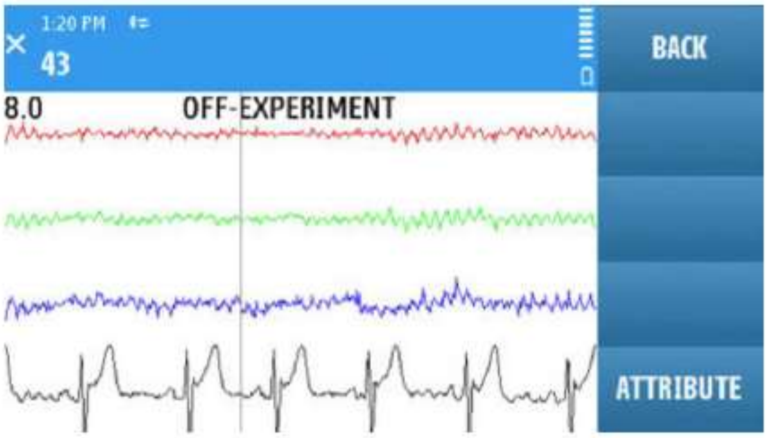
Custom IC Sensor Package

Bottom Sensing Plate

- Structure
  - The electrodes operates via capacitive coupling on top of hair.
  - Based on a custom VLSI integrated analog front-end circuit

System design and mobile application





- Data acqusition
  - 24bit delta-sigma ADCs(TI ADS1298), PIC24F low-power microcontroller, onboard Bluetooth module, two AAA batteries (10 hours working time)
- Mobile signal processing
  - Nokia N97 cellular phone (640x360 pixel 3.5 inch touchscreen LCD)
  - Canonical correlation analysis(CCA) : band-pass filter and correlation calculation

CCA

- CCA is a multivariable statistical method used when there are two sets of data, which may have some underlying correlation.
- It finds a pair of linear combinations, for two sets, such that the correlation between the two canonical variables is maximized.
- Consider two multidimensional random variables X, Y and their linear combinations $x = X^T W_x$ and $y = X^T W_y$ respectively.
- CCA finds the weight vectors, Wx and Wy, which maximize the correlation between x and y, by solving the following problem:

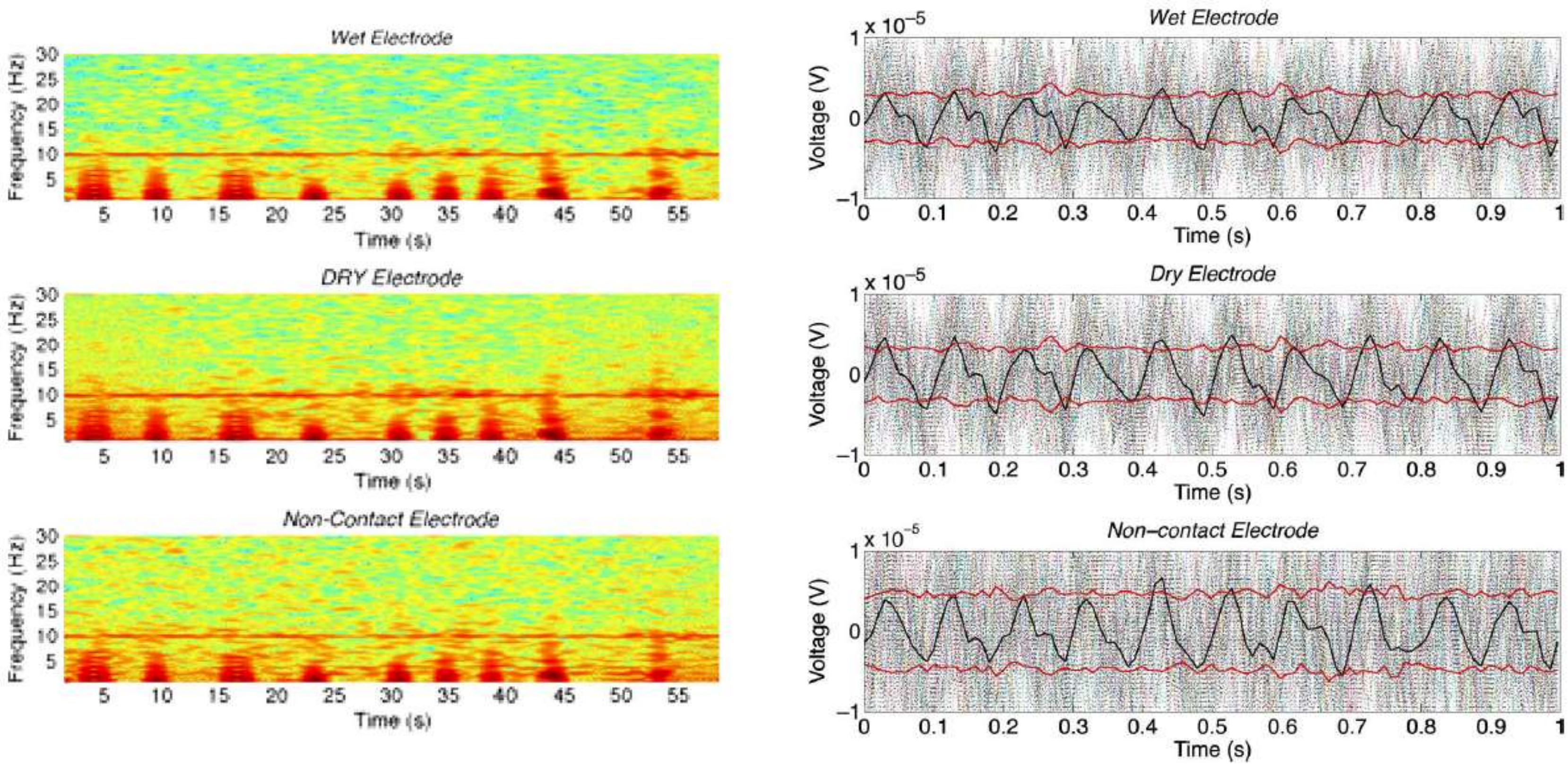
$$\max_{W_x, W_y} \rho(x, y) = \frac{E[x^T y]}{\sqrt{E[x^T x] E[y^T y]}} = \frac{E[W_x^T X Y^T W_y]}{\sqrt{E[W_x^T X X^T W_x] E[W_y^T Y Y^T W_y]}}.$$

- The maximum of *ρ* with respect to*Wx* and*Wy* is the maximum canonical correlation. Projections onto *Wx* and *Wy*, i.e. *x* and *y*, are called canonical variants.

Offline sensor benchmark

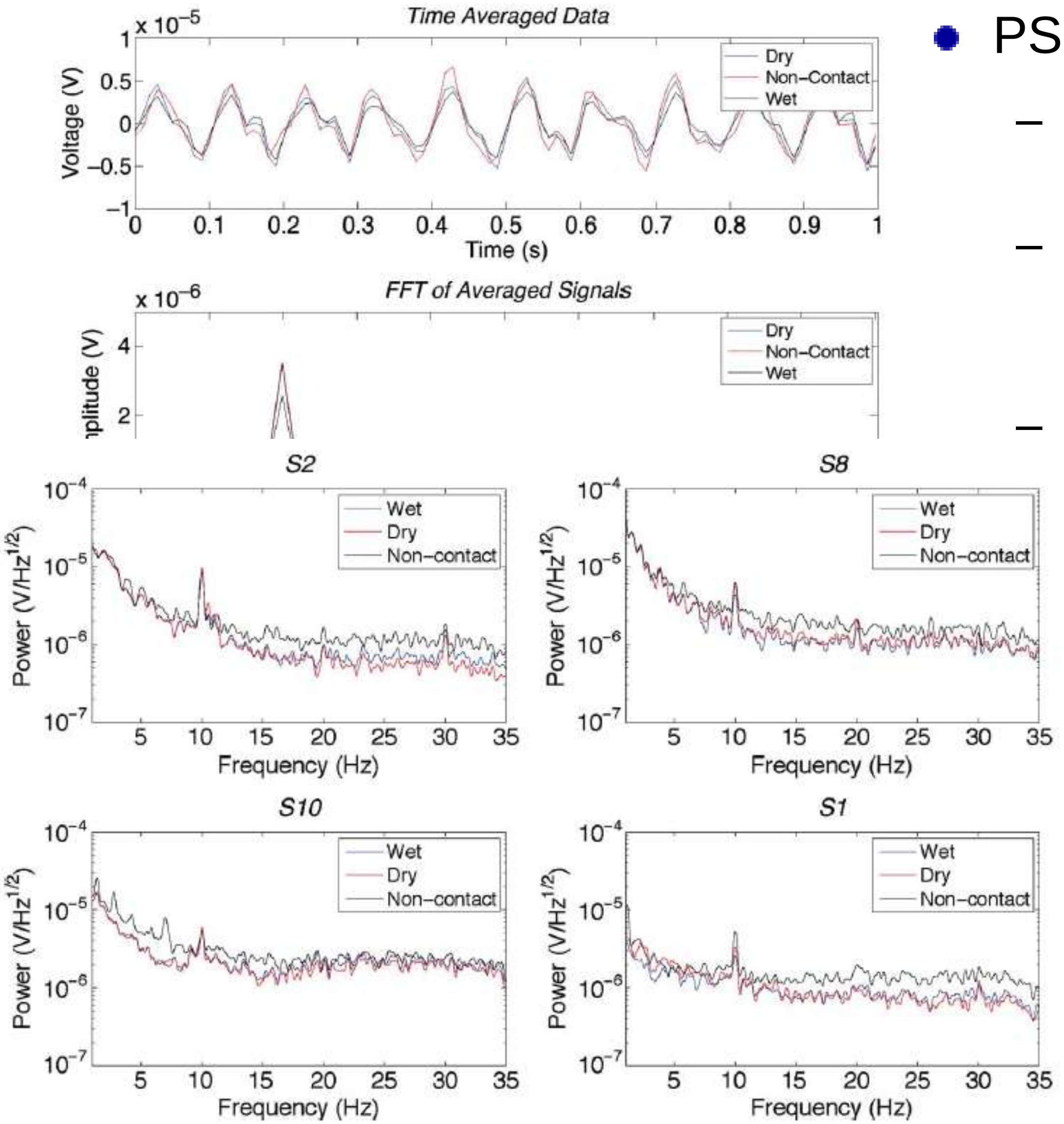
- Test setting
  - Comparison electrodes : wet Ag/AgCl electrodes, proposed dry electrodes, proposed non-contact electrodes
  - Three sensors array are attached in a triad over the occipital region as closely together as possible.
  - 10 subjects
  - Each subject gaze at a single SSVEP target stimulus(10Hz) displayed on a CRT monitor for a 1-min duration.
  - Each subject repeated this task three times, and the best dataset was used for analysis.

Offline sensor benchmark



- Result plots
  - Left spectrograms are one of the 60s trials shown 10Hz SSVEP stimulus.
  - Right graphs show detailed signals with the average in black, the standard deviation in red with the raw signals.

Offline sensor benchmark



- PSD
  - In the four subjects shown the 10Hz stimulus is clearly visible.
  - PSD from the wet electrode almost perfectly matches that from the dry electrode.
  - The PSD of the noncontact electrode's signals also shows the 10Hz stimulus. But, there is greater amount of broadband noise due to their high coupling impedance.

Offline sensor benchmark

TABLE I
SIGNAL CORRELATION BETWEEN DIFFERENT ELECTRODES

Subject	SSVEP Amplitude (μV)			Sensor Correlation			SNR (dB)		
	Wet	Dry	NC	Wet vs. Dry	Wet vs. NC	Dry vs. NC	Wet	Dry	NC
1	1.1	1.7	2.2	0.88	0.85	0.74	-15.16	-10.97	-10.36
2	3.7	3.7	3.2	0.98	0.88	0.85	-6.49	-7.00	-8.46
3	1.9	2.0	2.1	0.90	0.78	0.70	-11.71	-12.24	-12.96
4	2.2	2.2	2.4	0.97	0.80	0.78	-7.69	-8.09	-8.22
5	1.1	1.1	1.0	0.97	0.96	0.94	-12.24	-11.87	-13.05
6	1.6	1.2	1.4	0.75	0.71	0.55	-6.61	-10.49	-9.67
7	1.6	1.1	1.8	0.91	0.86	0.88	-14.33	-13.61	-10.72
8	2.5	3.4	3.5	0.93	0.73	0.70	-6.85	-5.17	-7.47
9	1.4	0.8	0.8	0.89	0.85	0.85	-13.08	-17.42	-17.64
10	1.4	1.8	1.4	0.95	0.57	0.59	-15.60	-13.29	-18.21
Mean	**1.8**	**1.9**	**2.0**	**0.91**	**0.80**	**0.76**	**-10.98**	**-11.01**	**-11.68**
STD	0.8	1.0	0.9	0.07	0.11	0.13	3.71	3.56	3.78

$$\mathrm{SNR} = 10\,\log_{10} \frac{\bar{X}(10\ \mathrm{Hz})^2_{\mathrm{rms}}}{var(x) - \bar{X}(10\ \mathrm{Hz})^2_{\mathrm{rms}}}.$$

- Correlation and SNR
  - Over half the subjects has a correlation of greater than 0.9 between the wet and dry electrodes.
  - Correlation values of the wet versus noncontact electrode were lower. But, half the subject had correlation values of above 0.8.

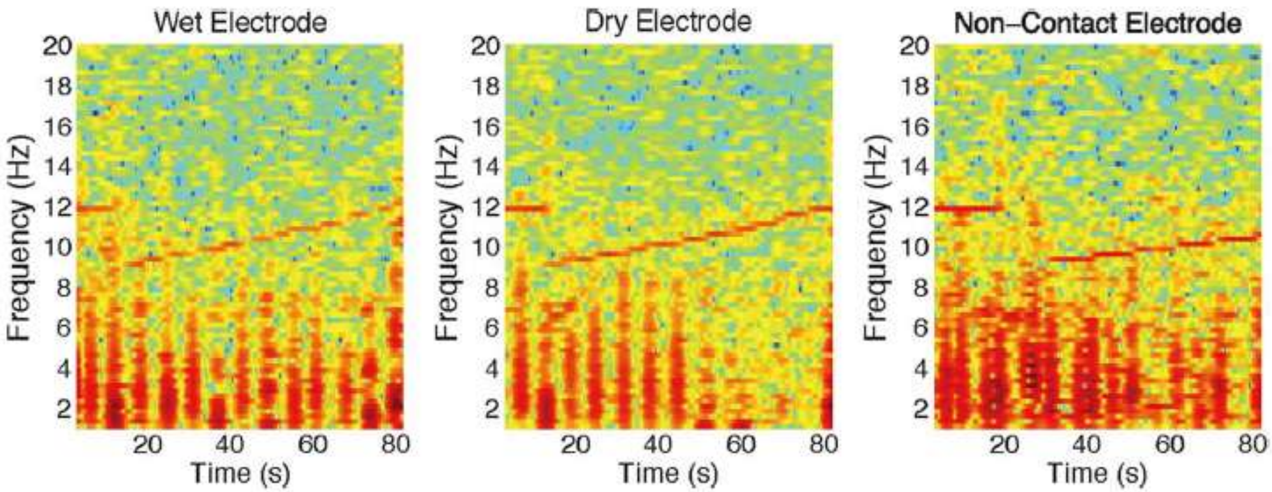
Online decoding test

- Test setting
  - Subjects 1 and 2 were recalled to perform an SSVEP phone dialing task using the mobile signal processing platform.
  - Procedure
    - 4s sliding window with 1s increments
    - Two consecutive decisions are constructed as a successful input and trigger an audio feedback to notify the subject
    - Noncontact electrodes
      - 6s sliding window with four consecutive decisions due to degraded SNR
  - Predetermined 12 digit sequence
  - Signal decoding performed using CCA analysis

Online decoding test

TABLE III
RESULTS FROM ONLINE BCI TESTS

		Accuracy			Detection Time (s)			ITR (bits/min)		
		Wet	Dry	NC	Wet	Dry	NC	Wet	Dry	NC
Subject 1	Trial 1	0.83	0.92	1.00	6.2	5.7	10.3	23.0	28.1	19.3
	Trial 2	0.83	0.83	1.00	5.9	5.8	9.7	23.9	22.6	20.5
	Trial 3	0.83	1.00	1.00	6.4	5.6	9.4	20.5	34.4	21.0
Subject 2	Trial 1	0.83	0.83	0.50	6.2	5.9	12.8	23.0	23.9	4.0
	Trial 2	0.83	0.92	0.75	5.9	6.3	9.7	23.9	27.3	11.9
	Trial 3	0.92	0.83	0.75	5.7	6.3	11.0	29.2	22.6	10.4
	Mean	**0.85**	**0.89**	**0.83**	**6.04**	**5.92**	**10.49**	**23.9**	**26.5**	**14.5**
	STD	0.03	0.07	0.20	0.26	0.31	1.29	2.90	4.52	6.85



Online decoding test

- Discussion of online test
  - In subject 1's spectrograms for the three different electrodes, the different SSVEP frequencies are clearly visible.
  - The wet and dry electrodes were could both be successfully used for BCI.
  - The dry electrode trials achieved superior performance to the wet electrode trials because the wet electrodes was tested last
  - Noncontact electrodes
    - Subject 1achieve 100% accuracy with noncontact electrodes because of longer detection window. But they achieve lower ITR (19 bits/min).
    - Subject 2 had difficulty with utilizing the noncontact electrodes due to thicker hair.

Conclusion

- Quantitative benchmarking show that dry and noncontact electrodes are capable of resolving SSVEP-type signals.
  – The dry electrode only shows a slight amount of signal degradation.
  – The noncontact electrodes show more signal degradation and susceptibility to movement artifacts.
- However, the online test demonstrate that both electrodes can be successfully utilized in BCI applications.
- The signal quality of noncontact electrodes is possible to still resolved with careful circuit design.