Dry and Noncontact EEG Sensors for Mobile Brain–Computer Interfaces

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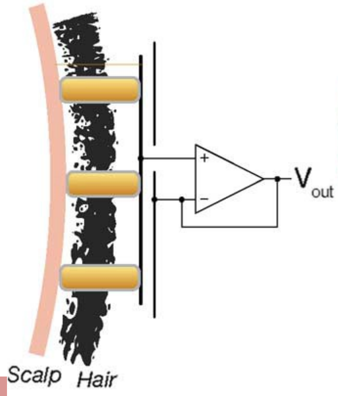
Introduction

- Brain-computer Interface
  - Brain–computer interface (BCI) is an emerging technology for interacting with the external world through a nonmuscular communication channel, completely independent of the motor pathways of the neural system.
- Research motivations
  - Conventional BCI systems have always relied on laboratory bound instrumentation and often require extensive subject preparation, including scalp abrasion, gels and a multitude of wired electrodes.
  - For truly mobile BCI systems to become a reality, significant improvements in the sensor hardware are still needed.
- Research goals
  - In this paper, they introduce dry/noncontact EEG electrodes and shown quantifying their performance within a SSVEP based BCI paradigm.

Discrete Dry Sensor

- Structures
  - Lower plate
    - It contains a set of spring-loaded pin contacts which can easily penetrate hair without the need for any preparation.
    - A male snap connector on the top side of the plate mates with it's female counterpart on a second PCB which contains the active electrode circuitry.
  - Active circuit PCB
    - High impedance signals offered by the dry contact are buffered with an off-the-shelf CMOS-input Opamp (National Semiconductor LMP7702).
    - The unity gain buffer, along with the shielded cabling, greatly reduces the effects of external interference.
- Pros and cons
  - Pros : Excellent signal quality, not require any preparation, no discomfort
  - Cons : greater amount of low-frequency drift due the high contact impedance and the less stable electrochemical interface



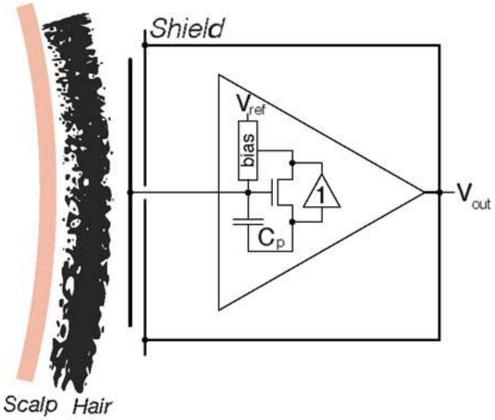
Dry Electrode Concept

Active Electrode Circuitry

Spring-loaded Dry Contact Pins

Integrated Noncontact Sensor

- Structures
  - They made new integrated noncontact sensor by the custom VLSI circuit implementation.
  - They designed fully bootstrap and shield the input node, starting from the active transistor, extending out to the bond pads and out to a specially constructed chip package.



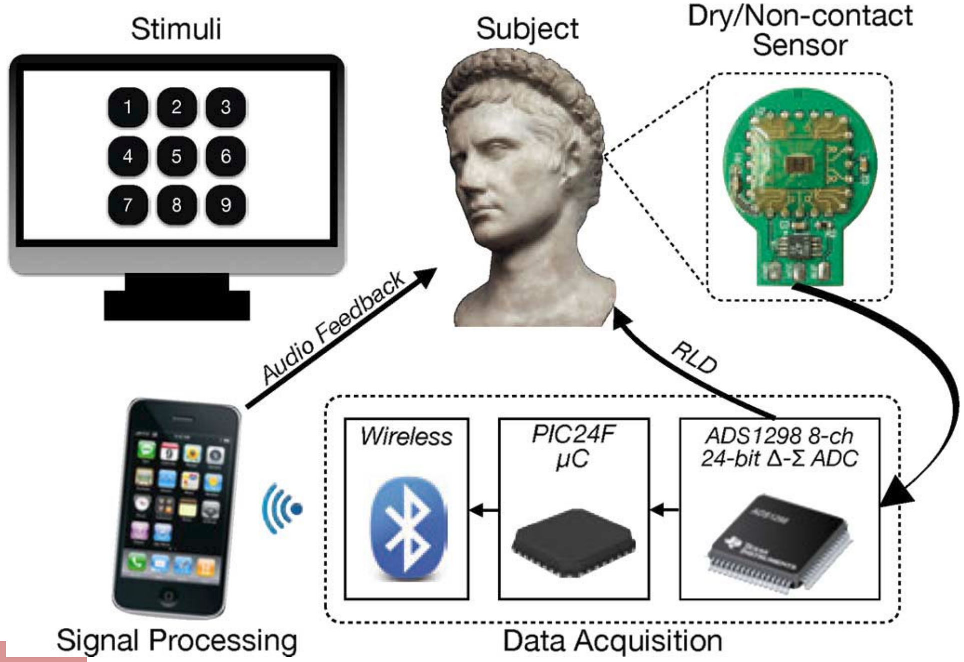
Integrated Non-contact Electrode Concept

Custom IC Sensor Package

Bottom Sensing Plate

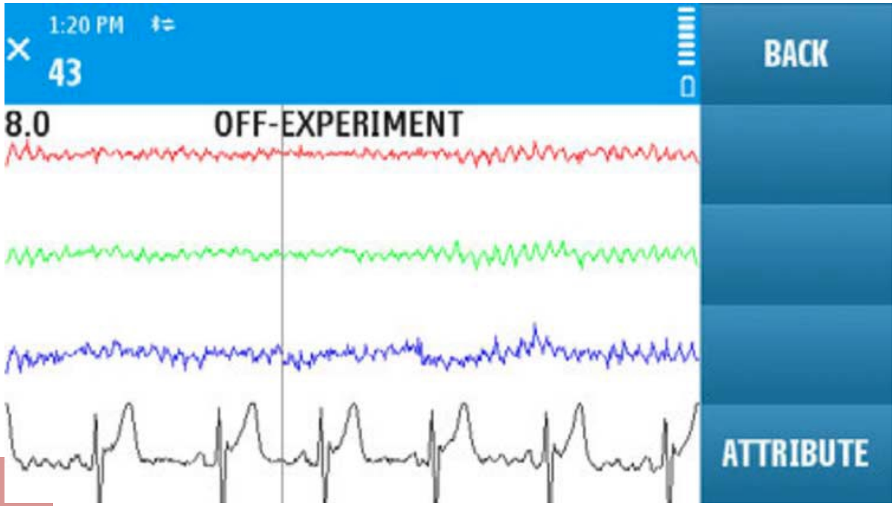
Wireless Data Acquisition

- System structure
  - Each of the sensors are connected to an octal, simultaneous sampling 24-bit ADCs (TI ADS1298).
  - The ADC is controlled by a PIC24F low-power microcontroller which acquires samples and dispatches the data to an onboard Bluetooth module.
  - The portable data acquisition box is powered by two AAA batteries, good for approximately 10 h of continuous wireless telemetry.



Mobile Signal Processing

- Mobile system
  - Signal processing of the EEG telemetry was accomplished on a Nokia N97 cellular phone.
  - A sample plot of EEG signals displayed on the phone's 640 * 360 pixel 3.5 inch touchscreen LCD
- Operation
  - The phone establishes a Bluetooth serial port connection with the data acquisition box and initially presents the user with raw telemetry.
  - EEG signal quality has been visually inspected by the user to be suitable for an experiment
  - After signal checking, the application can switch to canonical correlation analysis (CCA) mode for actual BCI experimentation.
  - In the analysis mode, a band-pass filter is applied to the signal to remove frequencies that are outside the SSVEP band (9–12 Hz).



Mobile Signal Processing

- Canonical correlation analysis (CCA)
  - The CCA algorithm attempts to obtain the maximum correlation between the signal from the three recording electrodes and a matrix of templates corresponding to the SSVEP stimulus frequencies.

- Online experiment paradigm
  - The online experiment involves a BCI with 12-possible selections corresponding to a number pad.
  - 12 SSVEP stimuli each with a corresponding template that is matched against the EEG signal.
  - For the experiments involving wet and dry electrodes, decisions are made on a 4 s sliding window that advances in 1 s increments.
  - Wet and dry electrodes : two consecutive decisions are construed as a successful input and trigger an audio feedback to notify the subject.
  - Non contact electrodes : increasing the 6s window with four consecutive decisions allowed for sufficient rejection of the extra noise.

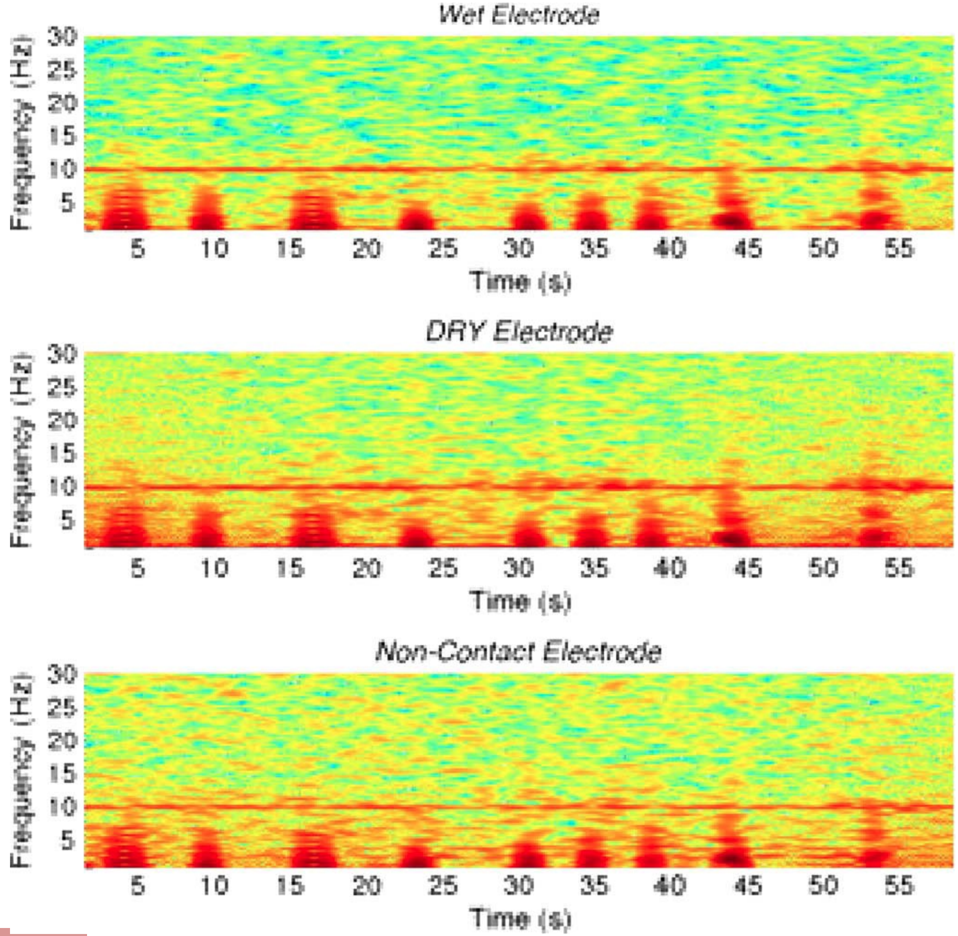
SSVEP Sensor Benchmark

- Benchmark methods
  - Each subject gaze at a single SSVEP target stimulus, displayed on a CRT monitor, at 10 Hz for a 1-min duration.
  - During the experiment, the SSVEP signal was decoded, in real-time, to verify the presence of the 10 Hz stimulus signal, but no feedback was presented to the subject.
  - Each subject repeated this task three times, and the best dataset was used for analysis.
  - Three sensors (wet, dry, and noncontact), were arrayed in a triad over the occipital region as closely together as possible.

- Analysis methods
  - First, how close the signal from dry and noncontact electrodes matches the signal from a “gold standard” wet electrode?
  - Secondly, it is also useful to calculate the ratio of signal versus noise (SNR) for each of the sensors

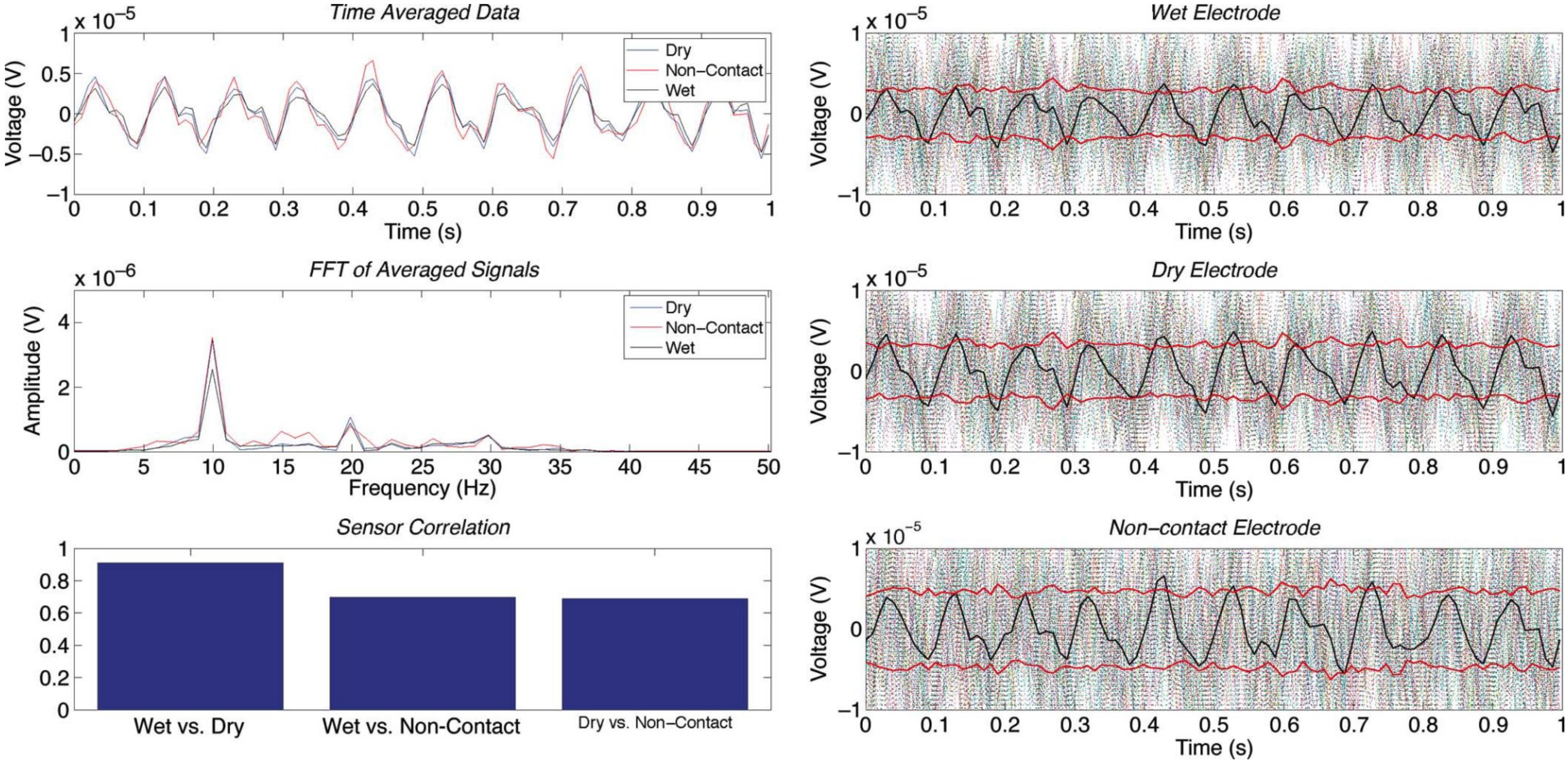
SSVEP Sensor Benchmark

- Graphical Results for 10Hz SSVEP stimulus
  - The spectrogram of the signal acquired from each sensor during one of the 60 s trials show that the SSVEP stimulus can be acquired by all three sensors.



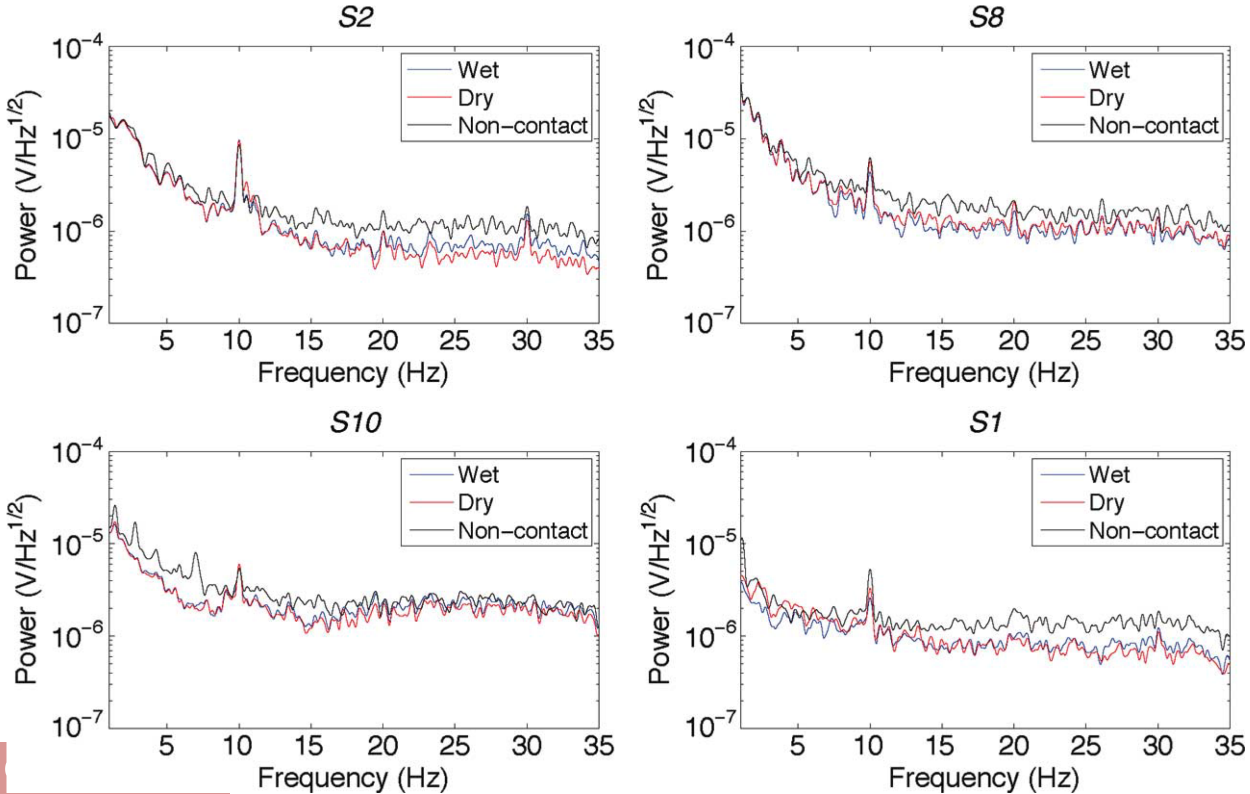
SSVEP Sensor Benchmark

- Graphical Results for 10Hz SSVEP stimulus
  - Averaging was performed over a 1 s period using a 0.5 s sliding window.
  - Detailed signals from each electrodes with the average in black, the standard deviation in red along with the raw signals.



SSVEP Sensor Benchmark

- Graphical Results for 10Hz SSVEP stimulus
  - In the four subjects shown in the figures, the 10 Hz stimulus is clearly visible.
  - The PSD from the wet electrode almost perfectly matches.
  - the noncontact sensor can exhibit a greater amount of both low-frequency drift as well as broadband noise due to the extremely high coupling impedance and sensitivity to movement artifacts.
  - In one subject S10 a pulse artifact can be seen in the spectra due to poor coupling of the noncontact electrode.



SSVEP Sensor Benchmark

- Analysis results
  - Since the SSVEP signal is small, band-pass filter applied for removing the majority of noise in the signal and it enables a correlation comparison between the three sensors specifically for the SSVEP paradigm.
  - To account for phase shifts of the SSVEP signal due to differences in electrode placement, the cross correlation (MATLAB xcorr) was used.
    - The maximum value was extracted for three comparisons
  - SNR was computed by examining the root-mean square amplitude of the fundamental 10 Hz tone, obtained via an FFT on the time averaged data , versus the background noise within the 8–13 Hz SSVEP band.

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

SSVEP Sensor Benchmark

- Analysis results
  - For the dry electrode, over half the subjects had a correlation of greater than 0.9 between the wet and dry electrodes, with three subjects achieving almost perfect correlation (0.978, 0.967, 0.975).
    - Only one subject exhibited a wet versus dry electrode correlation of less than 0.8.
  - For the noncontact electrode half the subjects had correlation values of above 0.8.
    - Only one subject had a correlation value of less than 0.7.
  - SNR is always well below 0 dB due to the small amplitude of the SSVEP signal relative to the background EEG and noise.

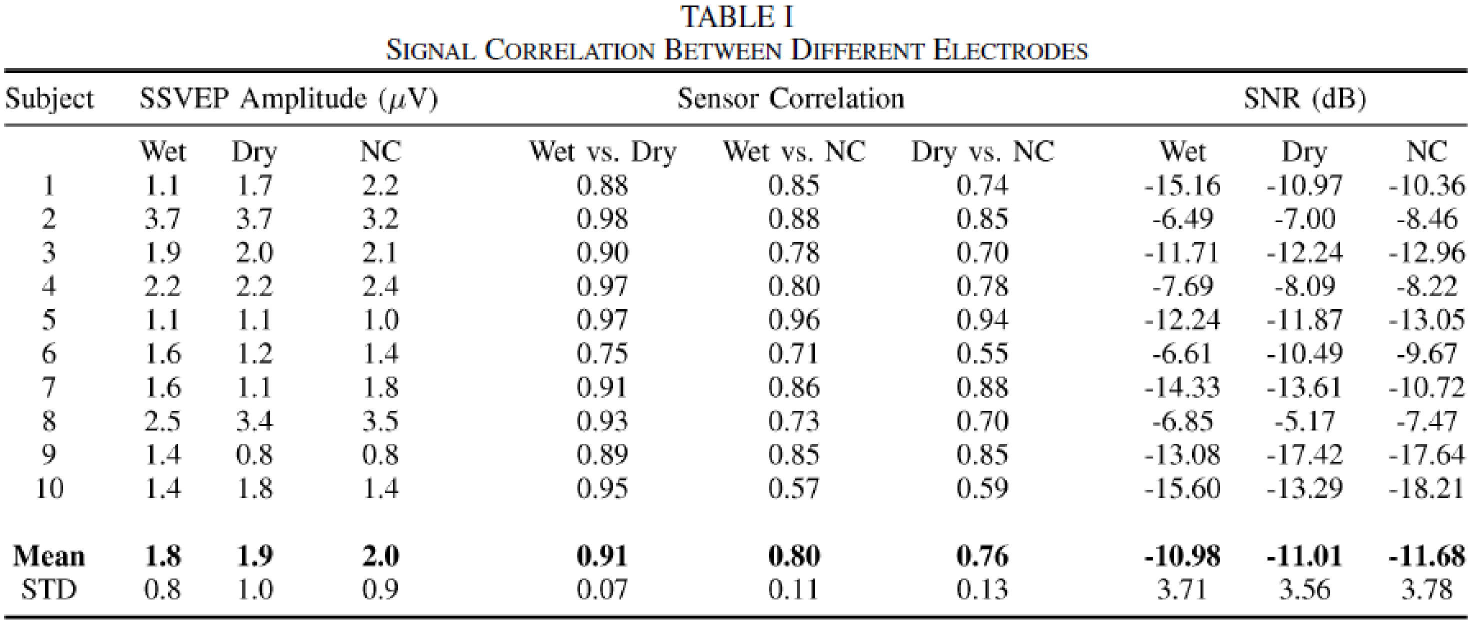


TABLE I
SIGNAL CORRELATION BETWEEN DIFFERENT ELECTRODES

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

SSVEP Sensor Benchmark

- Subband correlation results
  - In general, the correlation is fairly consistent irrespective of the bandwidth of interest.
  - At very low frequencies (<1 Hz) the correlation comparison becomes skewed due to drift noise.
    - Drift, such as sweat artifacts, typically have very large amplitudes.
    - if the two electrodes were drifting independently, then the correlation value would decrease towards zero.
    - On the other hand, if the common reference electrode was in poor contact and noisy, causing the two recording electrodes to drift synchronously, then the correlation value will increase towards one.

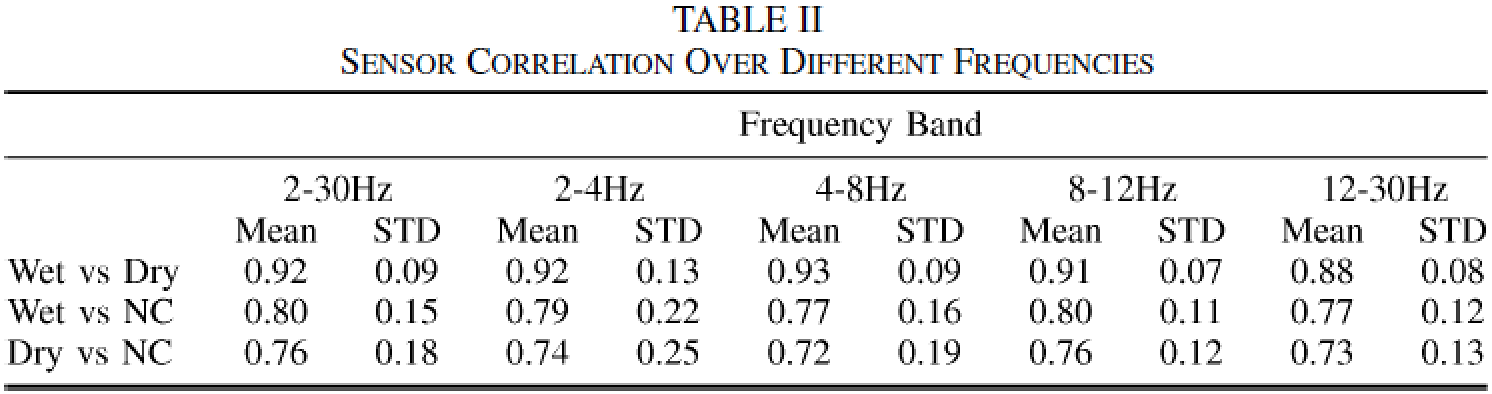


TABLE II

SENSOR CORRELATION OVER DIFFERENT FREQUENCIES

	Frequency Band									
	2-30Hz		2-4Hz		4-8Hz		8-12Hz		12-30Hz	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Wet vs Dry	0.92	0.09	0.92	0.13	0.93	0.09	0.91	0.07	0.88	0.08
Wet vs NC	0.80	0.15	0.79	0.22	0.77	0.16	0.80	0.11	0.77	0.12
Dry vs NC	0.76	0.18	0.74	0.25	0.72	0.19	0.76	0.12	0.73	0.13

Real-time Decoding Of SSVEP Signals

- Real-time experiment methods
  - To demonstrate their use in real-time BCI applications, subjects 1 and 2 were recalled to perform an SSVEP phone dialing task using the mobile signal processing platform.
    - The visual stimulator comprises a 21 inch CRT monitor (140 Hz refresh rate, 800 × 600 screen resolution) with a 4 × 3 stimulus matrix constituting a virtual telephone keypad which includes digits 0–9, BACKSPACE and ENTER.
    - The stimulus frequencies ranged from 9 to 11.75 Hz with an
    - interval of 0.25 Hz between two consecutive digits.
  - The online task consisted of entering a predetermined 12-digit sequence.
  - Signal decoding was performed using CCA analysis.

Real-time Decoding Of SSVEP Signals

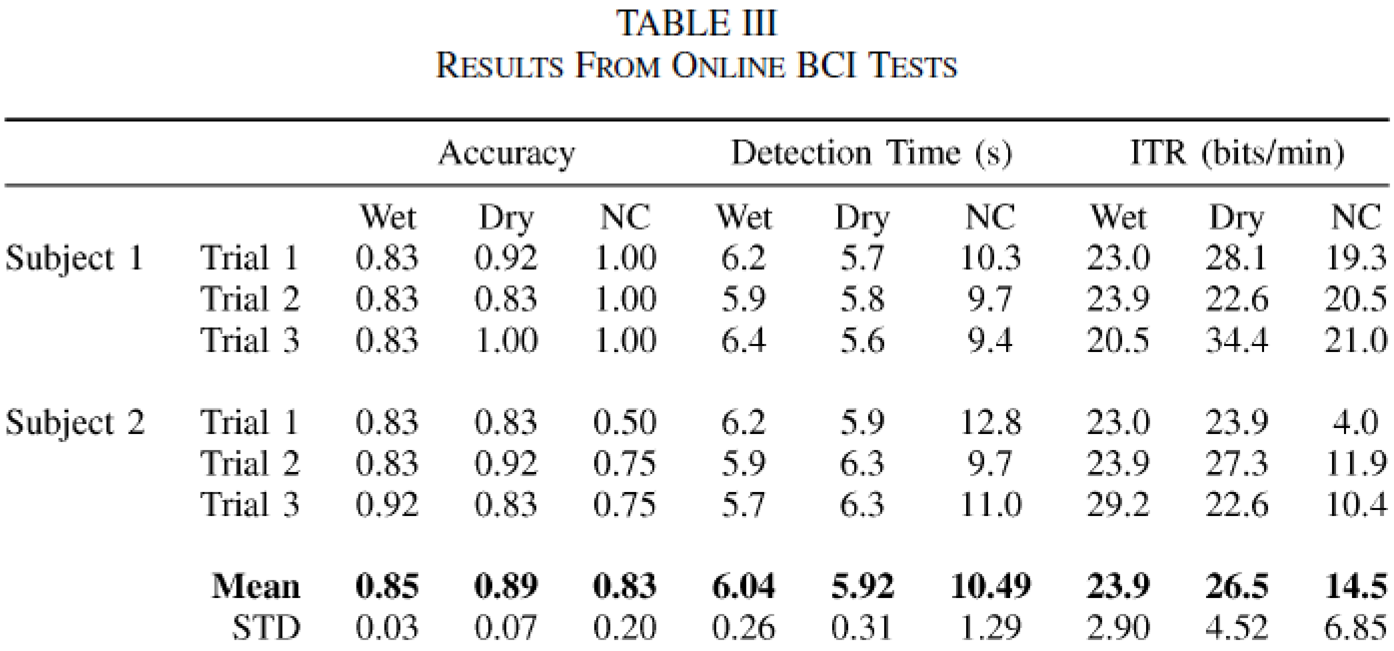
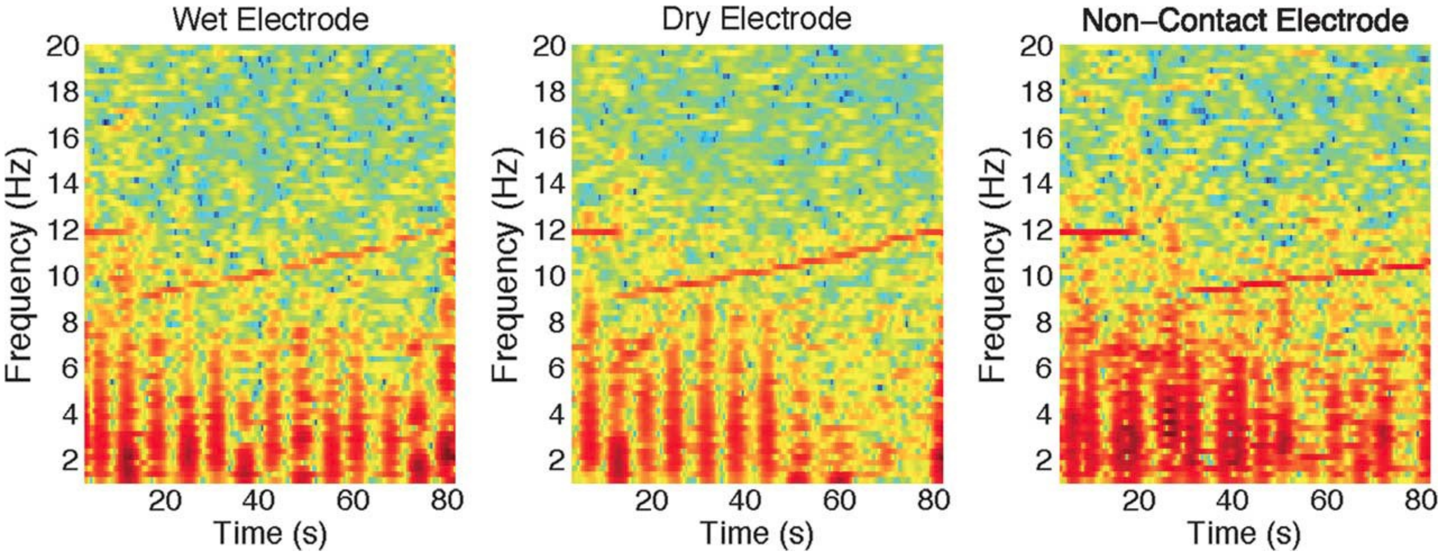


TABLE III
RESULTS FROM ONLINE BCI TESTS

		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



Real-time Decoding Of SSVEP Signals

- Real-time experiment Results
  - 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.