Overnight Non-Contact Continuous Vital Signs Monitoring Using an Intelligent Automatic Beam-Steering Doppler Sensor at 2.4 GHz

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***Abstract* — Doppler-based non-contact vital signs (NCVS) sensors can monitor heart rates, respiration rates, and motions of patients without physically touching them. We have developed a novel single-board Doppler-based phased-array antenna NCVS biosensor system that can perform robust overnight continuous NCVS monitoring with intelligent automatic subject tracking and optimal beam steering algorithms. Our NCVS sensor achieved overnight continuous vital signs monitoring with an impressive heart-rate monitoring accuracy of over 94% (i.e., within ±5 Beats-Per-Minute vs. a reference sensor), analyzed from over 400,000 data points collected during each overnight monitoring period of ~ 6 hours at a distance of 1.75 meters. The data suggests our intelligent phased-array NCVS sensor can be very attractive for continuous monitoring of low-acuity patients.**

I. INTRODUCTION

Non-contact vital signs (NCVS) measurement on the heart rate and respiration rate can reduce the patient's discomfort under monitoring, especially for burn victims or infants as it could be very uncomfortable for them to wear any sensor for an extended period. For the healthcare providers, having a reliable bio-sensing system that can measure and record the key vital signs of patients continuously can be quite valuable, as it can enable them to make better and informed decisions on patients. If the biosensor system is robust and can also make long-term overnight NCVS monitoring without disturbing the patients' sleep quality/patterns, and the system is also intelligent that can automatically discover abnormalities and alert the medical team for immediate and appropriate responses, that NCVS system may become invaluable in improving the patients' safety and quality of care, while also reducing the cost of healthcare. For example, it is well-known that for patients in general hospital wards, delays in treatment can lead to their clinical deterioration, but changes in their vital signs or mental function that happened before the deterioration are often overlooked [1]. This observation has led to the establishment of “rapid response teams” (RRTs) that are activated when a patient fulfills some predefined criteria based on vital signs checks and assessment of mental status, etc. often done by the nurse at the bedside; in addition, from these criteria the Early Warning Scoring Systems (EWS) were developed in hospitals. The justification for continuous vital signs monitoring is that suboptimal vital signs monitoring prior to an RRT referral may contribute to suboptimal patient outcomes clinically. Factors that may cause suboptimal patient monitoring include heavy workloads, late night shifts, lack of training or experience, etc. Therefore, we have developed our intelligent and robust Doppler-based continuous NCVS monitoring biosensor system that can be very attractive as a low-acuity patient's continuous monitor.

Doppler-based NCVS systems mostly use continuous wave (CW) or Ultra Wide band Doppler radar [2,3] to measure the periodic chest and heart movements of the patients [3-14]. We have recently reported a highly directive phased-array NCVS system with a phased delay module and external power amplifier that can perform automatic electronic beam steering with good beam steering angles for ~ 1 hour continuous NCVS monitoring in an office cubicle setting when the monitored subjects were sitting down [14,15]. In this work, for the 1st time, we report the impressive overnight NCVS testing results with our latest single-PCB NCVS system as shown in Fig. 1 to decrease the sensor size, minimize loss from connection cables, and improve the monitoring accuracy and robustness.

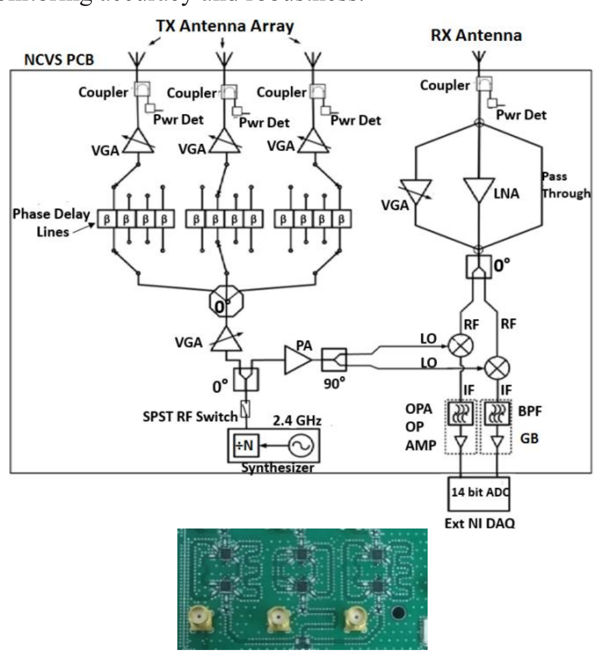

Fig 1: (TOP) The system block diagram of our single-PCB NCVS sensor; (Bottom) On-Board phase delay lines with SP4T switches

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II. Experimental Setup

Our latest single-PCB phased-array NCVS sensor shown in Fig 1 uses a 2.457 GHz CW signal generated by a low-phase noise synthesizer as the LO (local oscillator) signal for both transmit (TX) and receive (RX) paths via a SPST RF switch, respectively. The TX signal is amplified by a RF variable-gain amplifier (VGA) stage, and then go through a 3-way splitter. The split signals run through 3 SP4T switches to choose between the different phase delay lines for desired beam steering position to render one of the seven different beam steering angles. Once the three split TX signals are delayed by the desired amounts, they are fed into custom made helical antennas to provide highly directional TX/RX beam illumination on a subject's chest [8-11]. Our NCVS system employs a homodyne RX architecture, The RX signal is down-converted by the I/Q mixers to the baseband, and then filtered using a band-pass filter with cut-off frequencies of 0.1 Hz and 10 Hz, and then amplified using an on-board non-inverting op-amp. We use the LabVIEW program to perform instrumentation control and signal arc-tangent demodulation algorithms, and the data is collected via a NI USB 6009 DAQ at a sampling rate of 200 Hz. The vital signs data is digitally filtered, auto-correlated and evaluated using a FFT to determine their frequencies [12]. The NCVS system can automatically perform a sweep of each steering angle by selecting the digital logic on the phase delay lines. After completing all 7-angle sweeps, the angle with the highest Standard Deviation/Median ratio (i.e., Variance Ratio) is chosen as the optimal monitoring angle. The TX and RX antennas are fastened to the bottom of a wooden board, which is mounted at about 175 cm above the ground (see Fig 2). No circulator is used. For all NCVS tests conducted the volunteer subjects were made to lie down on their backs below the NCVS board on a mattress such that the center of their chests was aligned to the center of the middle TX antenna. For heart rate monitoring accuracy testing, the subject's heart rate was also measured by a piezoelectric contact-based finger sensor as reference during continuous NCVS monitoring. The nature of the study described in this paper does not require Institutional Review Board approval, in compliance with Institutional Policy.

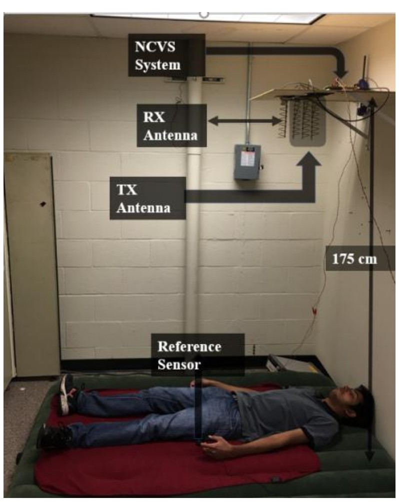

Fig. 2 Test setup for overnight continuous NCVS monitoring using our intelligent automatic beam-steering phased array NCVS sensor system.

III. Enabling Overnight Automatic NCVS Monitoring

To enable long-term continuous NCVS monitoring overnight during a subject's sleep where lots of natural, voluntary motions will occur, our latest single-PCB NCVS system features a method to detect and adapt to subject's movements, as well as a process for determining if the RX signal strength has degraded beyond an acceptable point to warrant a re-sweep. For example, if at any point during NCVS monitoring the system detects a large movement or a significant reduction in signal strength, the system will perform another sweep of the seven beam-steering angles and determine a new optimal angle for continuous monitoring. That is, movement detection and signal degradation algorithm runs in parallel with the main NCVS monitoring data collection to track the position of the subject and signal levels.

A specific example is shown in the flow chart of Fig. 3 that tries to determine if the signal strength has degraded over time, as the standard deviation of the arc-tangent signal is constantly measured over a 15 second period. If the Variance Ratio of the signal falls below 20 % of the original Variance Ratio measured during the sweep, a re-sweep is conducted. In-order to determine the motion of a subject, the Median value of the arc-tangent signal is constantly measured over a period of 15 seconds as well. If the value of arc-tangent signal does not fall in the range of Median +/- (Threshold * Median), the re-sweep is triggered. The threshold limits for movement trip were set at -1.75 and 0.75 (*i.e.,* a range of 250 % of the median [15]) so that movements of the arm, leg, and head as well as coughs and sneezes can be ignored, while the system can still detect larger movements such as a subject changing positions during monitoring. The power levels at each transmitter were measured at ~16.5 dBm and each TX VGA was set at 0 dB attenuation. The RX path has a VGA and it was also set with 0 dB attenuation on the LabVIEW GUI.

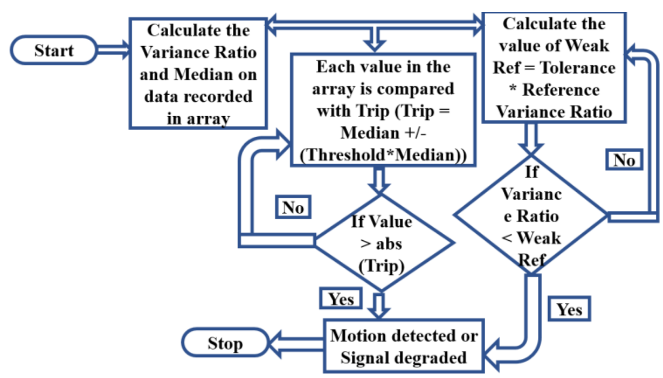

Fig. 3 Flow chart for motion detection and signal degradation for triggering an automatic re-sweep for overnight NCVS monitoring.

To test if our latest NCVS system is working as expected, we first performed a short 5-min sweep at each steering angle by manual steering and then with automatic steering, the data statistics and box plots for the monitoring accuracy for instantaneous heart-rate are shown in Table I and Fig. 4, respectively. Table I shows the 1, 2 and 5 BPM accuracies, Inter-Quartile Range and standard deviation obtained for all of the 7- steering angles, and for auto steered cases using angles with highest variance ratios calculated by the automatic beam-steering algorithm. We obtained over 95% accuracy (within 5 BPM) during the entire tests, validating our automatic steering algorithm should be working well.

Table I: Test statistics of manual vs. automatic beam steering using our NCVS system, validating automatic steering algorithms (5 min each sweep)

	Manual Steering Angle (°; from center)							Auto Steer
	-14.1	-10.1	-4.6	0	3.6	9.9	13.3	
1 BPM	74.6	81.1	95.1	96.0	97.8	86.2	71.2	97.4
2 BPM	84.6	83.2	95.9	98.4	98.9	91.1	80.7	97.6
5 BPM	88.5	85.4	97.0	98.7	98.9	95.2	82.6	98.7
IQR	0.96	0.36	0.21	0.55	0.42	0.68	0.75	0.29
Sta. Dev. (σ)	2.19	1.84	2.79	1.07	3.58	1.12	4.54	0.21

*IQR means inter-quartile-range.

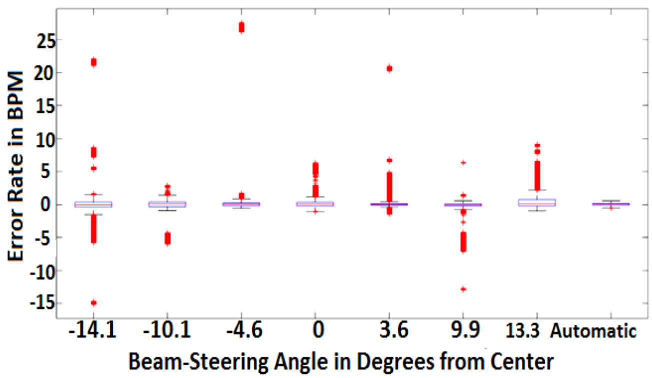

Fig. 4 Box plots for manual vs. automatic beam steering (the boxplot at far right) using our NCVS system, validating automatic steering algorithms (5 min each sweep).

To determine the feasibility of our system for overnight NCVS monitoring, we continued to conduct series of tests with 1-hour sweep each, manually for all the 7-steering angles. Later we have conducted 1-hour tests with our robust automatic beam-steering algorithm which detects the best beam-steering angle with highest variance ratio and low error rate per BPM as indicated in Fig 4. These 1-hour sweeps each on an average consisted of 80,000 data points. For these tests, we also obtained an accuracy of instantaneous heart-rate monitoring of ~ 94% within 5 BPM (data not shown for brevity), further indicating our system is able to perform long-term automatic and intelligent NCVS monitoring.

IV. Overnight NCVS Monitoring Data and Discussions

Finally, we took a series of roughly 6-hour overnight continuous NCVS monitoring tests. Each test had on an average of 410,000 data points. On an average, there were ~ 10 re-sweeps in total during the entire monitoring period, (each complete 7 angle re-sweep takes 350 s) which can be seen labeled in Fig. 5 with the overnight instantaneous heart-rate accuracy data plotted on the time scale. During the overnight test shown here, the subject under monitoring had various body movements which covered the entire mattress and the beam steering algorithm was able to pick up the best angle after the movement or after an event of signal degradation and provided an impressive overall instantaneous heart rate monitoring accuracy of over 94% within 5 BPM. As one can see in Fig. 5 there was a sizable drop in accuracy to ~75% during the period of 5252 to 6281 seconds (*i.e.,* for about 17 minutes), and this was because the subject was moving around and sleeping in the log position on-the-side instead of on-the-back. Fig. 6 also show the heart-rate monitoring accuracy data when it is averaged at a 1-min interval instead of comparing instantaneously every second as shown in Fig. 5. One can see this simple averaging of heart rate removed the huge spikes caused by natural movement artifacts and thus improved the heart-rate accuracy greatly to 96-97%; it also impressively tracks the reference heart rates to be within +/- 6 BPM for the entire overnight monitoring period!

Table II shows the interesting statistics for the 5 min, 1-hour, and overnight NCVS monitoring heart-rate accuracy data (instantaneous). Note for the 6-hour overnight monitoring data, we included here two sets of data measured on the same subject but tested with two slightly different automatic beam-steering algorithms to illustrate the importance of the selection of automatic steering algorithm on overnight monitoring accuracy. One can see the data collected using the Standard Deviation/Median ratio has a considerably better instantaneous heart-rate monitoring accuracy than the other one that used Standard Deviation/Mean for overnight monitoring (i.e., ~ 9-24% better). This somewhat surprising result suggests that due to the natural body movement during sleep causes large data outliers to skew up the Mean of the data statistics similar to what is shown in Fig. 5, and therefore it is wise to utilize Median rather than Mean for statistical analysis and automatic steering algorithms as shown in Fig 7. which contains the box plots of the data presented in Table II.

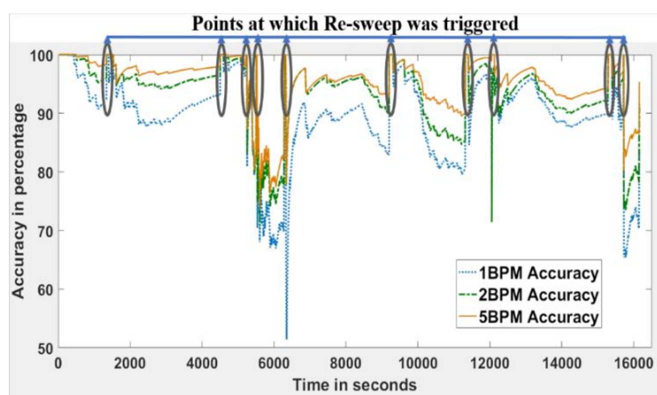

Fig. 5: Time scale instantaneous heart-rate monitoring plot for 1, 2 and 5 BPM accuracy obtained for a 6-hour overnight NCVS monitoring test.

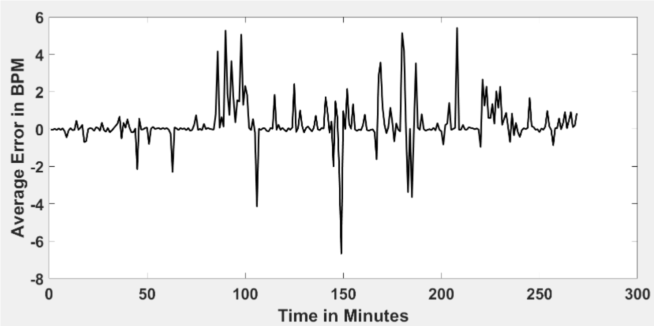

Fig. 6 Time scale heart-rate monitoring accuracy plot when the raw data is averaged in a one-minute interval for an overnight NCVS monitoring test.

Table II: Statistics for 5 min, 1-hour, and overnight NCVS monitoring of instantaneous heart-rate accuracy data; the 6-hour overnight data includes two algorithms using σ/Mean vs. σ/Median for automatic beam steering.

Beam Steering	**Automatic**			
Test Time	**5-min (σ/Median)**	**1-hour (σ/Median)**	**6-hour (σ/Mean)**	**6-hour (σ/Median)**
1 BPM	97.41	89.84	63.60	87.55
2 BPM	97.60	92.18	75.76	91.79
5 BPM	98.69	94.17	85.34	94.19
IQR	0.29	0.35	1.46	0.43
Sta. Dev. σ	0.21	2.91	9.19	3.12

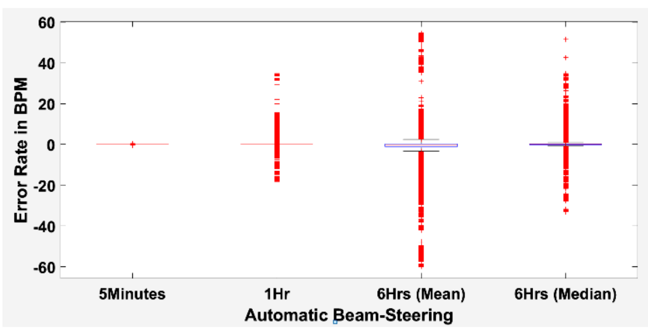

Fig. 7 Box plots for continuous NCVS monitoring with automatic beam steering for data shown in Table II

V. CONCLUSION

We have demonstrated that, for the 1st time to the authors' knowledge, an intelligent single-PCB Doppler-based phased-array NCVS system with automatic beam-steering, movement detection and signal degradation algorithms that is capable of continuous overnight NCVS monitoring. The sensor system achieved an impressive overnight instantaneous heart rate accuracy of over 94% (within 5 BPM), and the average heart rate taken over 1-min period even tracks within +/- 6 BPM of the reference heart rate data throughout the entire overnight monitoring period. We will continue to collect more overnight statistical monitoring data on our NCVS sensor before moving it into a clinical trial in low-acuity patient wards. We believe our NCVS system can provide continuous and reliable monitoring of heart rate, respiration rate, and bed motion for patients in many hospital settings, as well as in skilled nursing homes, in long term acute care facilities, in rehab units, and for at-home monitoring. We will also plan on improving the intelligence of our NCVS system by analyzing the trend of the overall/long-term continuous vital signs to provide alerts to the RRTs, and possibly to nurses' mobile phones to provide bed exit alerts for high fall risks patients, and even including a timer alert for turning patient to preventing bed sores, etc.

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