Millimeter-Wave Pulse Radar Scattering Measurements on the Human Hand

Sebastian Heunisch, Lars Ohlsson Fhager, and Lars-Erik Wernersson

***Abstract*—We investigate the backscattering of low-power millimeter-wave pulses (wavelets) on the human hand in order to determine the detection limit of scattering features. Using an in-house wavelet radar setup with a nominal spatial resolution of 2.29 cm, we measure a hand in three different postures: a flat hand, a fist, and a hand with raised index finger. For the latter, we are able to resolve backscattering from at least two different scattering centers, attributed to the heel of the hand and the finger. The effective radar cross section in the measurements was in the range from −29.5 to −35.1 dBsm. We demonstrate that detecting scattering features from the hand with an equivalent isotropically radiated power spectral density of −68.5 dBm/MHz is possible. This shows that, compared to most conventional radar systems operating close to the regulatory emission limits (13 dBm/MHz), the energy of the transmitted waveform can be significantly reduced. The result shows that low-power radar systems for gesture recognition are feasible using pulsed systems with ultrashort pulses and low duty cycles. This is key for integration in battery-powered devices.**

***Index Terms*—Gesture recognition, millimeter-wave radar, millimeter waves, pulsed radar, radar applications, radar cross-section (RCS) measurement, time-domain analysis.**

I. Introduction

ADVANCES in high-frequency integrated circuit technology make radar systems available for consumer applications beyond conventional motion sensors. Integration to a small form factor is important, and therefore frequency bands at millimeter-wave (mm-wave) frequencies, in particular the band around 60 GHz with a large available bandwidth [1], are of particular interest. Today, even battery-powered radar systems for short ranges are feasible. This opens up a variety of novel applications, for instance, gesture control in handheld and wearable devices.

Recently, several radar systems for gesture recognition have been proposed. Some approaches rely only on the Doppler profile of hand gestures [2], [3]. Other approaches additionally resolve gestures spatially [4]–[8], providing additional information for gesture recognition. Most systems use frequency-modulated continuous-wave radar, due to simplified transceiver design and high output power. For designing energy-efficient radars for battery-powered applications, duty cycling the system is key. Time-domain pulse generation techniques [9], [10] offer a direct way to realize those duty cycles in integrated implementations. Ideally, continuously running oscillators at the mm-wave frequency can be avoided by this approach. In a pulsed system, the signal-to-noise ratio is limited by the pulse energy, proportional to the amplitude and length of the transmitted pulses, and the wide bandwidth of the receiver. For low-power operation, the energy of the transmitted signal should be minimal, whereas still assuring that individual scattering centers on the hand can be detected. This can be solved by modulating the pulse in amplitude, frequency or phase, to increase the time-bandwidth product of the waveform.

In this letter, we use an in-house fabricated pulse generator [11] to investigate the scattering of mm-wave pulses (wavelets) on the human hand. We present measurements of the reflection from the human hand in three different postures: a flat hand (Posture A), a fist (Posture B), and a hand with raised index finger (Posture C). We show that a signal can be acquired with pulsed waveforms much weaker than the allowed emission limits in the 60 GHz band [1], which is commonly used as signal level for conventional radar systems. To the best of the authors' knowledge, this is the first measurement of ultrashort mm-wave pulses scattered on a human hand. High spatial resolution in our measurements enables the identification of features of the postures that are separated in down range. To quantify the backscattered signal from these features, we calculate their frequency averaged radar cross section (RCS). Our results show that, compared to previously presented gesture recognition systems, the transmitted energy can be reduced, whereas scattering feature detection is still possible. From that, we conclude that the design of battery-powered-radar systems for the recognition of dynamic hand gestures is possible.

II. Measurement System

The reflection of static hand gestures was measured with a time-domain wavelet radar setup. A block-level schematic of the measurement setup is shown in Fig. 1. Coherent mm-wave pulses (wavelets) in the 60 GHz band were generated with an in-house RTD-MOSFET wavelet generator. The pulse pattern of the generated wavelets is controllable by a digital input sequence, achieving a pulse length down to 25 ps [11]. In our measurements, a 10 Gb/s input sequence was provided by an Agilent N4906B BERT, resulting in a pulse length of 100 ps. The

Manuscript received March 30, 2019; revised May 2, 2019; accepted May 9, 2019. Date of publication May 15, 2019; date of current version July 3, 2019. This work was supported in part by the Swedish Foundation for Strategic Research (SSF), in part by the Swedish Research Council (VR), and in part by the Knut and Alice Wallenberg Foundation. *(Corresponding author: Sebastian Heunisch.)*

The authors are with the Department of Electrical and Information Technology, Lund University, 221 00 Lund, Sweden (e-mail: sebastian.heunisch@eit.lth.se; lars.ohlsson_fhager@eit.lth.se; lars-erik.wernersson@eit.lth.se).

Digital Object Identifier 10.1109/LAWP.2019.2917081

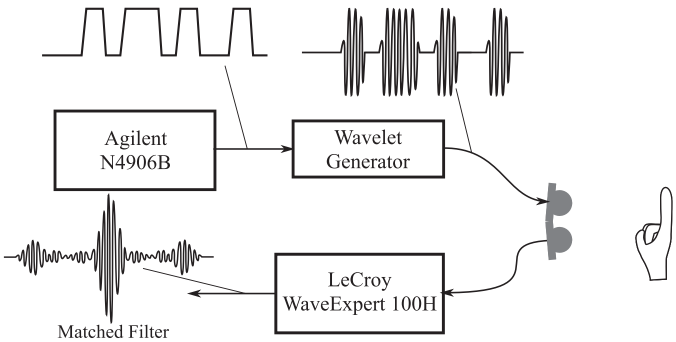

Fig. 1. Schematic of the measurement setup. A square wave signal from an Agilent N4906B BERT is fed to an in-house wavelet generator to generate a staggered pulse sequence. The received signal is recorded using a LeCroy WaveExpert 100 H equivalent-time sampling oscilloscope, and the matched filter response is calculated by the correlation of the received signal with a template.

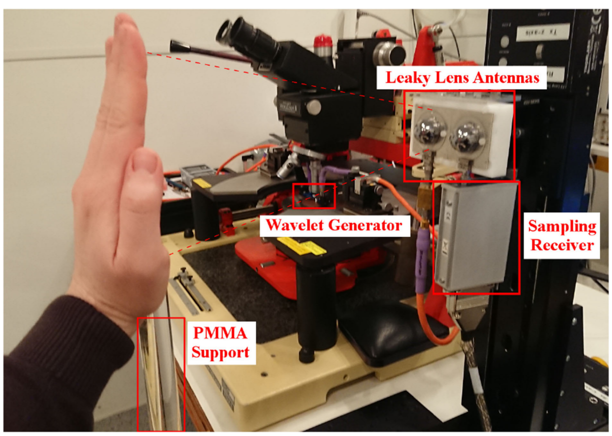

Fig. 2. Photograph of the measurement setup. The signal is generated by an in-house wavelet generator. The pair of wideband leaky-lens antennas are for transmitting and receiving. Reflection form hand postures at 250 mm distance from the antennas are recorded. The PMMA rod, located outside the main lobe of the antennas, is used to support the hand during gesture measurements.

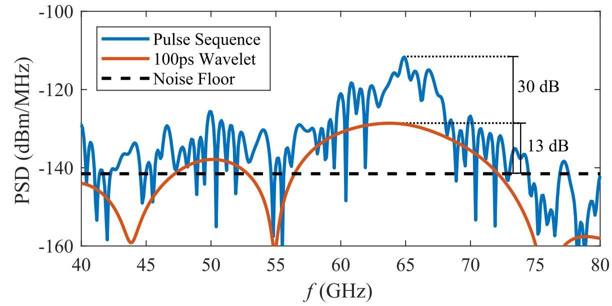

Fig. 3. PSD of waveforms backscattered on a metal reflector at 250 mm distance. The waveforms were acquired by averaging over 1000 measurements ($A = 1000$). The staggered pulse sequence (blue) gives a 17 dB higher PSD compared to a 100 ps wavelet (red). The noise floor for the acquisition settings used for the hand measurements ($A = 10$) is shown dashed.

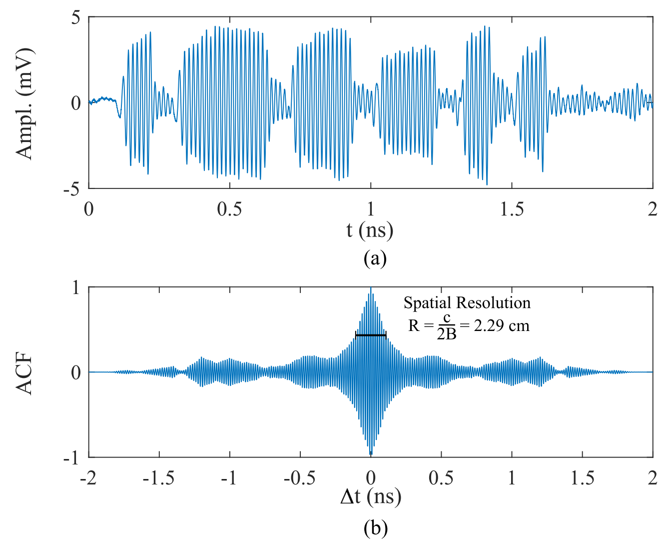

Fig. 4. (a) Staggered pulse sequence and (b) its ACF showing the matched filter response of the transmitted sequence.

used wavelet generator had an oscillation frequency of 65 GHz. A pair of nondispersive wideband leaky-lens antennas with approximately 16 dBi [12] was used for transmitting and receiving wavelets. The received signal was acquired directly using a LeCroy WaveExpert 100H sampling oscilloscope with a nominal bandwidth of 70 GHz. Hand postures were measured at 250 mm distance from the antennas. An acrylic glass (PMMA) rod was used as support for the hand to avoid unintentional movement as far as possible (see Fig. 2). Data of three hand postures (flat hand, fist, and the hand with raised index finger) were acquired in 1000 consecutive measurements. As reference, the reflection of a 300×300 mm^2 metal plate was recorded. Additional details about the setup, also used for material characterization, are available in [13].

III. Signal Acquisition

Decreasing the energy of the transmitted waveform is one way to reduce the power consumption of a radar system. However, the received energy needs to be sufficient to distinguish the signal from the receiver noise. Limited peak power in pulsed radar systems requires longer waveforms to carry sufficient energy. To realize high-resolution waveforms, the signal is typically modulated in amplitude, frequency, or phase. Controlling the length of the waveform allows to adapt the transmitted energy to the application-specific needs. In this section, we investigate the detection limit for reflections from the human hand and the requirements for the measurement system.

To evaluate the link budget of our measurements, we analyze the power spectral density (PSD) backscattered on the reference metal plate. Measurements of the PSD for a signal reflected on a metal reflector in 250 mm distance are shown in Fig. 3. For a 100 ps wavelet, the PSD is less than -128.6 dBm/MHz. Naturally, a longer wavelet would result in a signal with higher PSD but lower bandwidth, and therefore lower spatial resolution. For our measurements, we used a pulse sequence [14] to increase the transmitted energy without significant loss of resolution. The used sequence and its autocorrelation function (ACF) are shown in Fig. 4(a) and (b), respectively. The nominal resolution for the waveform is $\Delta R = 2.29$ cm. The measured maximum PSD for the pulse sequence is -111.7 dBm/MHz. In our setup, this corresponds to an equivalent isotropically radiated PSD (EIRP SD) of -68.5 dBm/MHz. The used PSD is much lower than in most other mm-wave radar systems. Typically, radar sensors are operated close to the allowed transmission limits. In the draft of the European regulations [1], the maximum PSD is 13 dBm/MHz in the 60 GHz band and -20 dBm/MHz for the out-of-band emissions. In the following, we will show that identifying scattering features of the human hand is possible with a signal with low PSD, as used in our system.

The level of the backscattered signal is dependent on the RCS of the object under test. The RCS, σ_{Hand}, of the human hand has been reported to be in the range of -45 dBsm$< \sigma_{\text{Hand}} <$ -20 dBsm [15]. To estimate the expected backscattered power from the posture, we compare σ_{Hand} to the RCS of our metal reflector, σ_{Ref}. Since the metal plate used is large compared to the wavelength and the illuminated area, we approximate the reflector as perfect mirror. Its RCS at distance $R = 250$ mm is given by $\sigma_{\text{Ref}} = \pi R^2 \approx -7$ dBsm. The expected power level from the hand postures is therefore -13 to -38 dB lower than the reflection of the reference reflector.

For measurements with the sampling oscilloscope, fast acquisition and low noise floor need to be traded off. Waveforms are obtained by multiple sampling in different periods of the signal at interleaved sampling steps. Incoherence due to movement during the acquisition interval distorts the signal and prevents detection. The noise floor also depends on the acquisition speed. Our sampling oscilloscope has an input impedance of 50 Ω and a noise level of approximately $V_{\text{RMS}} = 3\,\text{mV}$. This translates to a noise PSD of

$$S_{xx} = \frac{\Delta t}{A} \cdot \frac{V_{\text{RMS}}^2}{50\,\Omega} \qquad (1)$$

where Δt is the sampling step and A is the number of averages taken during acquisition. Empirically, we achieved good results with an effective sampling step $\Delta t = 0.39$ ps and $A = 10$. This results in a noise floor of -141.5 dBm/MHz. For the used waveforms, this gives us about 30 dB dynamic range (see Fig. 3). This shows that features 30 dB weaker than the reference can be detected, i.e., features down to a RCS of -37 dBsm. The effective acquisition rate in these measurements, limited by the processing speed of the sampling oscilloscope, was approximately 10 Hz. Our calculations show that low-energy pulsed waveforms with low duty cycles can be used to detect scattering from the human hand. This is a key factor for the development of battery-powered gesture recognition systems.

IV. Measurement Results and Discussion

The measured hand postures (flat hand, Posture A, fist, Posture B, and hand with raised index finger, Posture C) and the corresponding backscattered signals are shown in Fig. 5. Spatially resolved features for the postures are determined from the measurements.

Posture A shows one feature at the position of the hand. The distorted shape of the matched filter response [compare to the

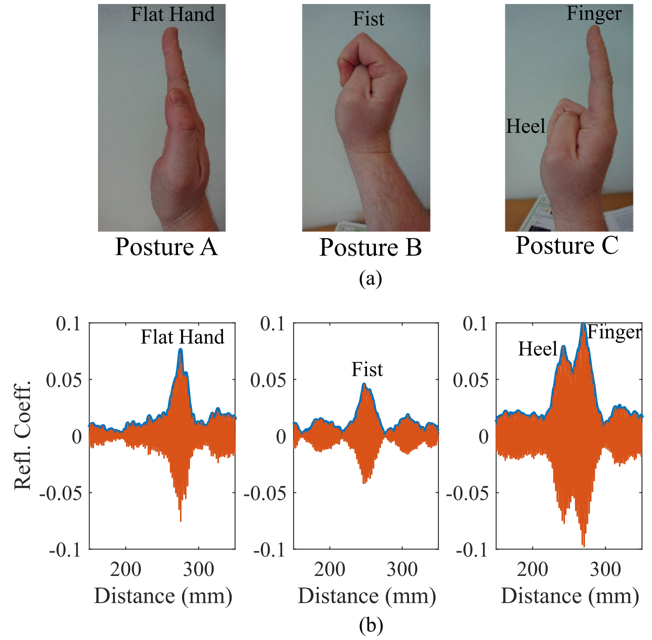

Fig. 5. (a) Radar reflection of different static hand postures: flat hand (Posture A), fist (Posture B), and hand with raised index finger (Posture C). (b) Range-dependent reflection coefficient for the measured postures. In Posture C, reflections from the heel and the index finger can be resolved.

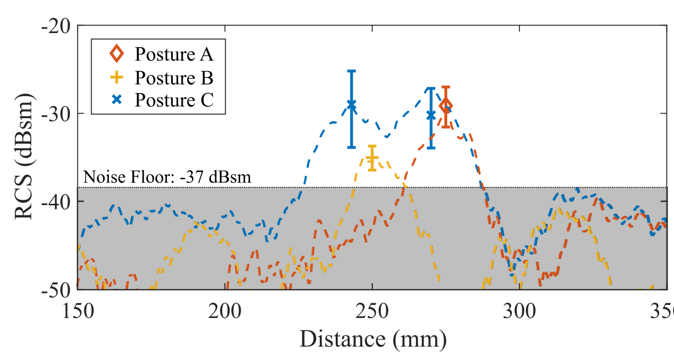

Fig. 6. RCS of the hand in the measured postures. Mean values and confidence interval for 1000 measurements are shown. The flat hand (Posture A) has a mean RCS of -29.8 dBsm. The fist's (Posture B) mean RCS is -35.1 dBsm. For Posture C, the heel of the hand has a mean RCS of -29.5 dBsm, and the index finger -30.6 dBsm.

ACF in Fig. 4(b)] might indicate reflections from multiple scattering centers, which cannot be resolved by the used waveform. Similarly, the reflection from Posture B shows only one single feature. Posture C, by contrast, shows two clear features separated by approximately 25 mm. We attribute these two features to the reflections of the long side of the finger and the heel of the hand facing the antenna, respectively.

To quantify the amplitude of the measured reflection, we estimate the frequency averaged RCS [16] of the postures in the measured position. The RCS is estimated in reference to the reflection obtained by the measurement of the metal plate ($\sigma_{\text{Ref}} = -7$ dBsm). The RCS for the three postures in the measured position, including mean and confidence interval for all 1000 measurements, is shown in Fig. 6. In general, we expect the RCS of the postures to be strongly dependent on the exact positioning and incidence angle. For our measurements, we determine a mean RCS of -29.8 dBsm for Posture A. Posture B shows the lowest RCS with -35.1 dBsm. For Posture C, the variance of the peak RCS is highest, indicating a strong influence of the positioning of the hand. In this posture, we determine the RCS of the heel as -29.5 dBsm and the RCS of the finger as -30.6 dBsm. The values are in the range of previously reported hand RCS values in *E*-band (60–90 GHz) [15].

V. Conclusion

We have measured the scattering of mm-wave radar pulses on the human hand using an in-house mm-wave radar system. Three different hand postures (the flat hand, the fist, and the hand with raised index finger) were investigated. We show detection of scattering features with an EIRP spectral density of -68.5 dBm/MHz. This is much lower than the regulatory emission limits at which most conventional radar systems operate. We conclude that the power consumption of radar-based gesture recognition systems can be reduced by using ultrashort pulsed signals with low duty cycles. Furthermore, the high spatial resolution of our pulsed waveform enables identifying characteristic features in the acquired matched filter response of the postures, for instance, the time delay between the finger and the heel of the hand. The RCS of the features, found in the measured postures, was in the range of -29.5 to -35.1 dBsm. Our result demonstrates the feasibility of the detection of the human hand using pulsed mm-wave radar systems and is relevant for the design of a low-power gesture recognition system. In future work, we plan to use a real-time receiver in our system. By applying pulse-Doppler processing, we will be able to acquire down range and velocity information simultaneously. This will enable gesture recognition and classification.

References

[1] *Short Range Devices (SRD) - Radio Equipment to be Used in the 40 GHz to 246 GHz Frequency Range*, European Telecommunications Standards Institute (ETSI), Harmonised European Standard EN 305 550, Oct. 2017.

[2] Y. Kim and B. Toomajian, "Hand gesture recognition using micro-Doppler signatures with convolutional neural network," *IEEE Access*, vol. 4, pp. 7125–7130, 2016.

[3] T. Sakamoto, X. Gao, E. Yavari, A. Rahman, O. Boric-Lubecke, and V. M. Lubecke, "Hand gesture recognition using a radar echo IQ plot and a convolutional neural network," *IEEE Sens. Lett.*, vol. 2, no. 3, pp. 1–4, Sep. 2018.

[4] J. Lien *et al.*, "Soli: Ubiquitous gesture sensing with millimeter wave radar," *ACM Trans. Graph.*, vol. 35, no. 4, pp. 142:1–142:19, Jul. 2016.

[5] Z. Zhang, Z. Tian, and M. Zhou, "Latern: Dynamic continuous hand gesture recognition using FMCW radar sensor," *IEEE Sens. J.*, vol. 18, no. 8, pp. 3278–3289, Apr. 2018.

[6] S. Ryu, J. Suh, S. Baek, S. Hong, and J. Kim, "Feature-based hand gesture recognition using an FMCW radar and its temporal feature analysis," *IEEE Sens. J.*, vol. 18, no. 18, pp. 7593–7602, Sep. 2018.

[7] Y. Sun, T. Fei, F. Schliep, and N. Pohl, "Gesture classification with handcrafted micro-Doppler features using a FMCW radar," in *Proc. IEEE MTT-S Int. Conf. Microw. Intell. Mobility*, Apr. 2018, pp. 1–4.

[8] F. Khan, S. K. Leem, and S. H. Cho, "Hand-based gesture recognition for vehicular applications using IR-UWB radar," *Sensors*, vol. 17, Apr. 2017, Art. no. 833.

[9] N. Deparis, A. Siligaris, P. Vincent, and N. Rolland, "A 2 pJ/bit pulsed ILO UWB transmitter at 60 GHz in 65-nm CMOS-SOI," in *Proc. IEEE Int. Conf. Ultra-Wideband*, Sep. 2009, pp. 113–117.

[10] M. Egard, M. Arlelid, L. Ohlsson, B. Borg, E. Lind, and L. E. Wernersson, "$In_{0.53}Ga_{0.47}As$ RTD-MOSFET millimeter-wave wavelet generator," *IEEE Electron Device Lett.*, vol. 33, no. 7, pp. 970–972, Jul. 2012.

[11] L. Ohlsson, P. Fay, and L.-E. Wernersson, "Picosecond dynamics in a millimetre-wave RTD-MOSFET wavelet generator," *Electron. Lett.*, vol. 51, no. 21, pp. 1671–1673, 2015.

[12] I. Vakili, L. Ohlsson, M. Gustafsson, and L.-E. Wernersson, "Wideband and non-dispersive wavelet transmission using leaky lens antenna," *Electron. Lett.*, vol. 49, no. 5, pp. 321–322, Feb. 2013.

[13] S. Heunisch, L. Ohlsson, and L. E. Wernersson, "Reflection of coherent millimeter-wave wavelets on dispersive materials: A study on porcine skin," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 4, pp. 2047–2054, Apr. 2018.

[14] C. Kaiteris and W. L. Rubin, "Pulse trains with low residue ambiguity surfaces that minimize overlapping target echo suppression in limiting receivers," *Proc. IEEE*, vol. 54, no. 3, pp. 438–439, Mar. 1966.

[15] P. Hügler, M. Geiger, and C. Waldschmidt, "RCS measurements of a human hand for radar-based gesture recognition at E-band," in *Proc. German Microw. Conf.*, Mar. 2016, pp. 259–262.

[16] L. Li, A. E. C. Tan, K. Jhamb, and K. Rambabu, "Characteristics of ultra-wideband pulse scattered from metal planar objects," *IEEE Trans. Antennas Propag.*, vol. 61, no. 6, pp. 3197–3206, Jun. 2013.