Quantum advantage in microwave quantum radar

A central goal of any quantum technology consists in demonstrating an advantage in their performance compared to the best possible classical implementation. A quantum radar improves the detection of a target placed in a noisy environment by exploiting quantum correlations between two modes, probe and idler. The predicted quantum enhancement is not only less sensitive to loss than most quantum metrological applications, but it is also supposed to improve with additional noise. Here we demonstrate a superconducting circuit implementing a microwave quantum radar that can provide more than 20% better performance than any possible classical radar. The scheme involves joint measurement of entangled probe and idler microwave photon states after the probe has been reflected from the target and mixed with thermal noise. By storing the idler state in a resonator, we mitigate the detrimental impact of idler loss on the quantum advantage. Measuring the quantum advantage over a wide range of parameters, we find that the purity of the initial probe-idler entangled state is the main limiting factor and needs to be considered in any practical application.

While quantum entanglement can enhance the performance of several technologies such as computing, sensing and cryptography, its widespread use is hindered by its sensitivity to noise and losses. Even when entanglement has been destroyed\(^ {1,2} \), some tasks still exhibit a quantum advantage \( Q \), defined by a \( Q \)-time speedup, over any classical strategies. A prominent example is quantum radar\(^ {3} \), which enhances the detection of the presence of a target in noisy surroundings. To beat all classical strategies, Lloyd\(^ {3} \) proposed to use a probe initially entangled with an idler that can be recombined and measured with the reflected probe. Observing any quantum advantage requires exploiting the quantum correlations between the probe and the idler. It involves their joint measurement\(^ {4} \) or at least adapting the idler detection to the outcome of the probe measurement\(^ {5} \). In addition to successful demonstrations of such quantum illumination protocols at optical frequencies\(^ {6,7} \), the proposal of a microwave radar\(^ {8,9} \), closer to conventional radars, gathered a lot of interest. However, previous microwave implementations\(^ {10-16} \) have not demonstrated any quantum advantage as probe and idler were always measured independently\(^ {10-16} \). In this work, we implement a joint measurement using a superconducting circuit and demonstrate a quantum advantage \( Q > 1 \) for microwave radar. Storing the idler mitigates the detrimental impact of microwave loss on the quantum advantage, and the purity of the initial entangled state emerges as the next limit\(^ {20} \). Whereas the experiment is a proof-of-principle performed inside a dilution refrigerator, it shows some of the inherent difficulties in implementing quantum radars such as the limited range of parameters where a quantum advantage can be observed or the requirement for very low probe and idler temperatures.

We focus on the simplest radar protocol, where the goal is to detect whether a target is present with a minimum number \( M \) of attempts. Each attempt corresponds to using a single microwave mode in time-frequency space to probe the target, with the constraint that the probe contains a fixed number \( N_S \) of signal photons on average (Fig. 1a) and is detected in a noise background of \( N_N \) photons. We consider that all other parameters are known: target position, speed and reflectivity \( \kappa \).

Several metrics can quantify the performance of a radar. We choose the error exponent defined as \( \mathcal{E} = \lim_{M \to \infty} \frac{1}{M} \log P_{\text{error}}(M) \), which means that the error probability \( P_{\text{error}}(M) \) is logarithmically equivalent to \( e^{-\mathcal{E}M} \). For simplicity, we assume no previous knowledge on the target state: initially the target is present with a probability \( 1/2 \).

Under the assumptions of the central limit theorem, the number of required attempts to reach a given error probability scales as \( 1/\mathcal{E} \). The
Quantum advantage can thus be defined as $Q = E/E_{cl}$, where $E_{cl}$ is the error exponent of the best classical strategy.

Given a certain probe state, the largest achievable error exponent for any measurement apparatus is the so-called quantum Chernoff bound\(^{24-26}\). De Palma and Boregaard\(^{22}\) showed that the best classical strategy (that is, without quantum memory) is to use a coherent state as a probe, which gives an optimum $E_{cl} = \frac{\kappa N}{4\sqrt{N}}$. This limit is asymptotically reached by a homodyne measurement in the large noise ($N_\nu \gg 1$) limit\(^{25}\). Quantum strategies rely on initially entangling the probe with an idler\(^{1}\). The quantum Chernoff bound for quantum radar is $E_{max} = \frac{\kappa N_\nu}{N_\kappa}$ in the low signal $N_\nu \ll 1$, high noise $N_\kappa \gg 1$ regime\(^{24}\), which shows that the quantum advantage is at best $Q_{max} = 4$ for radars. Effectively, it can be reached using one mode of a two-mode squeezed vacuum state (TMSV) to illuminate the target\(^{24,25}\). However, there is no known detector that can reach this advantage $Q_{max} = 4$ without a global joint measurements of $M$ modes of all attempts.\(^{27,28,30-32}\). Using simpler pairwise joint measurements instead\(^{24,27,28}\), it is nevertheless possible to reach $Q = 2$ with $E_{pair} = \frac{\kappa N_\kappa}{2N_\nu}$.

Here we implement pairwise joint measurements using a superconducting circuit\(^{29,31}\) that also generates the TMSV states\(^{29-31}\), and stores the idler mode while the signal probe travels. We then experimentally determine the error exponent of this quantum radar for various signal and noise photon numbers. To ensure a fair determination of the experimental quantum advantage $Q$, the absolute best classical error exponent $E_{cl}$ must be determined. Previous microwave radar experiments managed to exceed the error exponent of one instance of classical radar\(^{30-32}\), but could not break the classical upper bound $E_{cb}$. A central challenge of the experiment thus consists of performing precise calibrations of the target and radar parameters $\kappa$, $N_\nu$ and $N_\kappa$.

**Microwave quantum radar implementation**

Our superconducting device contains two resonators: a signal resonator whose lifetime is set by its coupling to a transmission line and a much longer-lived idler resonator. The circuit is operated at 15 mK (Fig. 1b). The signal resonator, which emits and receives the probe signal, has a frequency $\omega_0/(2\pi) = 10.20$ GHz and is coupled to a transmission line at a rate $\gamma/(2\pi) = 25$ MHz. The idler resonator has a frequency $\omega_0/(2\pi) = 3.74617$ GHz and a decay rate of $\gamma/(2\pi) = 40$ kHz. The two resonators are coupled by a Josephson ring modulator (JRM, purple in Fig. 1b)\(^{36-38}\).

We start each of $M$ detection attempts by first applying a pump tone at a frequency $\omega_p = \omega_0 + \omega_1$ for 28 ns. This tone generates a TMSV state between the idler and the signal modes. The latter quickly exits the target, with reflectivity $\nu_\kappa$, in a thermal environment with mean photon number $\nu_\kappa$. A receiver processes all reflected signals and decides whether the target is present or not. Quantum probes can be initially entangled with an idler\(^3\). The quantum Chernoff bound for quantum radar is $E_{max}$\(^{22}\). De Palma and Boregaard\(^{22}\) showed that the best classical strategy (that is, without quantum memory) is to use a coherent state (purple) generating and decoding entangled pairs between signal mode (orange) and idler mode (blue). A transmon qubit (grey) completes the joint measurement. The entangling pump and thermal noise background are injected through a directional coupler into the signal resonator port. A Pulse sequence of the quantum radar experiment. The phase difference $\phi$ and delay $\tau_d$ between pump pulses, as well as the gain $G$ of the second pump pulse can all be tuned. The dashed box represents the measurement by the qubit of the effective photon number $\nu$ in the idler resonator for quantum radar but can be replaced by other photocounting schemes for calibration purposes (Supplementary Information Section 2).
with \(\langle N^{\text{yes/no}}\rangle\) and \(\sigma(N^{\text{yes/no}})\) the average effective photon number and its standard deviation when the target is present or absent. For each value of the signal \(N_S\) and noise \(N_N\) we numerically fine tune the values \(v_n\) to maximize the error exponent.

**Tuning up the quantum radar**

The exploitation of quantum correlations between signal and idler also requires finely tuning the pump pulse that recombines these modes. In contrast to the pump amplitude, the delay \(\tau_d\) and phase offset \(\phi_d\) between the pump pulses (Fig. 1c) can be chosen by operating the radar without added noise (\(N_N = 0\), and at the largest signal setting (\(N_S = 0.1\)). With the target present, we measure the average number of photons in the idler mode after the first squeezing operation \(N_{I,1\text{,yes}}\) and the second phase \(N_{I,2\text{,yes}}\) (Supplementary Information Section 2).

Figure 2a shows the cosine dependence of the ratio \(N_{I,2\text{,yes}}/N_{I,1\text{,yes}}\) as a function of the phase difference \(\Delta \phi = \phi_d - \phi_0\) between the two-mode-squeezing operations for a delay \(\tau_d = 86\) ns. The phase \(\phi_0 = -1.898\) corresponding to the maximal signal, depends on the electrical delay of the target and detuning of the pump. For the quantum radar experiment, we operate at \(\Delta \phi = 0\). The cosine dependence originates from an interference. In fact, our experiment implements a new kind of SU(1,1) interferometer\(^{34,40,41}\), where one of the arms that host the signal is tuned to a stationary mode. In this particular case, the asymmetric loss probability \(\kappa\) on one arm prohibits witnessing any remaining entanglement. We optimize \(\tau_d\) at \(\Delta \phi = 0\) by measuring how many extra photons are in the idler resonator after the second squeezing operation when the target changes from absent to present. This idler population increases \(N_{I,2\text{,yes}} - N_{I,2\text{,no}}\) is maximum for \(\tau_{d\text{opt}} = 86\) ns; see Fig. 2b that corresponds to the propagation delay of the signal to and back from the target.

The joint measurement can be further optimized by tuning the amplitude of the second pump, which can be recast as a gain \(G\) of the second two-mode squeezing operation. An expression for the optimal gain \(G\) is known for a given set of \(N_S, N_N\) and \(\kappa\) (ref. 5 and Supplementary Information Section 5), but we choose to empirically tune the gain \(G\) to compensate for the non-idealities of our setup. We set \(N_S\) and \(N_N\) to particular values and measure the error exponent \(\mathcal{E}\) for several values of \(G\). For the settings of Fig. 3, it reaches a maximum \(\mathcal{E} = 2.9(2) \times 10^{-5}\) for a gain of about \(\mathcal{G} = 1.015\), which is close to the prediction by ref. 5 of \(\mathcal{G} = 1.016\).

**Quantum advantage and inherent limitations**

To compute the quantum advantage \(Q = \mathcal{E}/\mathcal{E}_{\text{cl}}\), we now need to carefully calibrate the three parameters that set \(\mathcal{E}_{\text{cl}}\): the signal photon number \(N_S\), the injected noise photon number \(N_N\), and target reflectivity \(\kappa\). Each parameter is determined during the same experimental run, using a dedicated protocol.

The signal photon number is set by the first squeezing operation, in which the circuit acts as a phase-preserving amplifier of gain \(G_0\). For the settings of Fig. 3, it reaches a maximum \(\mathcal{E} = 3.53(4) \times 10^{-2}\) and \(N_N = 10.8(3)\). Each point is obtained using 15 series of 5 \times 10^5 tries. After each series, \(N_S\) and \(N_N\) are recalibrated. The green dashed line shows the quantum Chernoff bound providing the upper bound on the error exponent of any classical radar under the same conditions. The error bars and the coloured area represent the uncertainties (Supplementary Information Section 6). The inset shows the raw measurements for the highlighted point. For each possible outcome \(m\), the table shows the fraction of occurrences where \(m\) is found with the target being present or not, as well as the four values of \(v\) that are used in equation (1) to reach the highest error exponent. At this point, the quantum advantage is \(Q = 1.2(1)\).

\[N_S = 3.53(4) \times 10^{-2}, N_N = 10.8(3)\]
exponent that can be reached using coherent illumination $\varepsilon_{cl} = 2.1(1) \times 10^{-5}$. This quantum radar thus beats the best possible classical one by a factor $Q = 1.2(1)$, on par with what was achieved in optics. Note that taking into account the non-zero reflectivity when the target is absent would only lead to a slightly better quantum advantage as $\varepsilon_{cl}$ would decrease by about 1%. The quantum advantage we observe is obtained for a small signal photon number $N_s$ and a large noise photon number $N_n$. To determine the domain in the $N_s, N_n$ parameter space where a quantum advantage can be observed, we reproduce this measurement for various values of $N_s$ and $N_n$, and identify the maximal quantum advantage $Q$ as a function of receiver gain $G$, with the results shown in Fig. 4a. As these measurements and their associated calibrations take at least a few hours per point, we explore only a subset of the parameter space. Besides, the error exponent $\varepsilon_Q = kN_s/N_n$ gets smaller and smaller as $N_s$ increases or $N_n$ decreases so that it requires a longer measurement time.

From this measurement it appears that the quantum advantage increases with $N_n$, as expected. Guha and Erkmen23 also predict that $Q$ increases at low $N_n$ until reaching its maximum values of $Q = 2$. In our experiment, we observe that $Q$ diminishes when $N_n$ becomes too small.

We find that this behaviour originates from the non-zero initial thermal populations $N_{th}^{th}$ and $N_{th}^{th}$ of the signal and idler modes, respectively50. A model (Supplementary Information Section 4) taking $N_{th}^{th}$ and $N_{th}^{th}$ into account and using an idealized version of our photocounting measurement is shown in Fig. 4a and qualitatively reproduces the experimental results in Fig. 4a. However, we note that the model systematically underestimates the measured quantum advantage. While the origin of this discrepancy remains an open question, the modelling of the measurement of the effective photon number $\nu$ could be a likely culprit. Note that for this figure, we set $N_{th}^{th}$ to be $2 \times 10^{-2}$, which qualitatively reproduces our result better than the most pessimistic value of $5 \times 10^{-4}$ used in Fig. 3 to demonstrate a quantum advantage. In Fig. 4b, we evaluate this model for different values of $N_{th}$ and reveal how the window of signal photon number that show a quantum advantage $Q > 1$ shrinks, then disappears as $N_{th}$ increases.

We thus find that this thermal population is a major limitation in our experiment, contrary to idler loss. In our case, the latter only lowers the error exponent by $1 - e^{-\varepsilon_f} \approx 2\%$. Conclusion

We have demonstrated an advantage of quantum radar versus classical radar in the microwave domain. The experiment reveals the crucial importance of the purity of the TMSV state used to illuminate the target. Beyond the loss of idler photons, this limitation imposes a stringent upper bound on the idler temperature. The experiment makes clear that using this quantum advantage in practical settings is a tremendous challenge. For instance, strategies that perform non-adaptive separate (where the observables are determined before the experiment) measurements of signal and idler at room temperature and use postprocessing to extract correlations between the two21–24 cannot show a quantum advantage $Q > 1$ (refs. 4, 5). Our work shows how superconducting circuits can provide quantum enhanced sensing in radar. Whereas this exact scenario of quantum radar has limited applications25–31, it paves the way to demonstrations of other protocols measuring the range32 or velocity of a target4. Besides, our joint measurement could be replaced by a measurement of the signal followed by a feedback to the idler, which gives hope for an open air version of the quantum enhanced radar with a room temperature target. Another route consists of realizing a memory for many idler modes, using superconducting cavities3 or spin ensembles46, to go beyond $Q = 2$ (refs. 5, 26). Using quantum correlations for enhanced sensing can also be applied to other research. For dark matter searching, it would be interesting to apply our demonstration to axion detection47. For quantum communications, the quantum radar can be recast as the signalling of a bit of information (target present or not) through a noisy communication channel beyond the classical Shannon limit48–50. Finally, the origin of a quantum advantage without residual entanglement is still a fascinating puzzle worth exploring further51–53.

Online content

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Author contributions
R.A. performed the experiment and analysed the data. R.D. provided additional support for the experiment and analysis. T.P. fabricated the superconducting circuit and R.A. fabricated the target. R.A., R.D., A.B. and B.H. designed the experiment. B.H. supervised the project. All authors wrote the manuscript.

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