Bandwidth increase through distributed atomic receivers in a Rydberg vapour cell

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The data transfer capacity of a communication channel is limited by the Shannon-Hartley theorem and scales as \( \log_2(1 + \text{SNR}) \) for a single channel with a given power signal-to-noise ratio (SNR). We implement an array of atom-optical receiver antennas in a single-input-multi-output (SIMO) configuration by using spatially distributed probe light beams. The data capacity of the distributed receiver configuration is observed to scale as \( \log_2(1 + N^2 \times \text{SNR}) \) for an array consisting of \( N \) receivers. Our result is independent on the modulation frequency, and we show that such enhancement of the bandwidth cannot be obtained by a single receiver with a similar level of combined optical power due to the saturation of the SNR. We investigate both theoretically and experimentally the origins of the single channel capacity limit for our implementation.

I. INTRODUCTION

In recent years there has been a growing interest in atom-based techniques for the detection of microwave (MW) electric fields [1, 2], that allow for calibration free SI-traceable measurements [3] achieving ultra-high sensitivity exceeding 55 nV cm\(^{-1}\) Hz\(^{-1/2}\) [4]. Rydberg atoms have been identified as particularly suitable for such measurements of radio-frequency (RF) electric fields due to their high polarizabilities and large microwave (MW) transition dipole moments [5]. Advances in Rydberg based field measurements have been accompanied by applications in atom-based communication technology. The fundamental working principles of analog and digital communication, where a baseband signal is modulated onto an electromagnetic MW carrier wave, have recently been demonstrated in a range of Rydberg-based systems. Examples include amplitude modulation (AM) [6–10], frequency modulation (FM) [11, 12] and phase detection [13, 14], as well as multiple bands [11], multiple channels [15], and multiple species [10]. Common to these methods is the broad carrier frequency range from tens of MHz to several THz that can be covered by the numerous Rydberg states of a single atomic species.

Rydberg receivers generally rely on the phenomenon of electromagnetically induced transparency (EIT) [16] in a three-level system, where a coupling laser field renders an otherwise opaque atomic medium transparent to a probe laser field due to quantum interference. If the three-level atomic system is coupled to a fourth level via an RF transition, the Autler-Townes (AT) effect [17] alters the transmission of a light field. For an RF electric field, which is modulated with a signal measuring the modulation of the transmitted light allows to directly retrieve the signal. In contrast to conventional receivers that rely on band-specific electronic components, Rydberg based receivers benefit from a direct and real-time read out of information, and physical reconfiguration is not necessary when the carrier frequency is varied. Also, the received information is encoded in a light field, i.e. a laser beam, suitable for long-distance transport via a fiber-link.

One of the most important figures of merit for any communication system is the channel capacity \( C \), which gives the amount of information that can be passed through a communication channel in a period of time without error. For a channel with a bandwidth (BW) its upper limit is defined by the Shannon-Hartley theorem [18] as

\[
C = \text{BW} \times \log_2(1 + \text{SNR}) \quad \text{(bits/s).}
\]  

The crucial parameter for a communication system is therefore the power signal-to-noise ratio (SNR) at a given bandwidth, which has to be maximised in order to attain the maximal channel capacity. A common method for increasing the data transmission capability is to establish multiple channels using, e.g., multiple identical receiver antennas while keeping the transmission power the same. This so called single-input-multi-output (SIMO) arrangement is formally equivalent to a single receiver with an increased SNR, and therefore a higher data capacity is achieved. For \( N \) receiver antennas the data capacity increases with [19]

\[
C_A(N) = \text{BW} \times \log_2(1 + N^2 \times \text{SNR}).
\]  

In this paper we investigate the scalability of the data capacity of atomic radio receivers. As opposed to conventional antennas, Rydberg receivers can work in the electrically small regime [20]. Therefore it is possible, in principle, to improve the data capacity by increasing the atomic density within the receiver volume. In a vapour cell environment, this usually means that one needs to increase the vapour pressure within the cell by heating it which introduces significantly larger Doppler width and collisional broadening of the transition. Alternatively, the size of the receiver can be expanded, for example, by extending the optical path length – this has the consequence that the background optical depth, which does not contribute to the signal, rises, causing the detected

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probe light field at 780 nm passes through an acousto-optic modulator (AOM), which is driven by a multitone frequency source. Up to four diffracted beams at frequencies \( f_1, f_2, f_3 \) and \( f_4 \) can be generated simultaneously. The diffracted beams impinge on a lens which generates parallel beams with \( \sim 70 \mu m \) radii in its focal plane, see Fig. 1(c). The probe and coupling beams are counter-propagating under an angle of \( \sim 2^\circ \) to create spatially separated (> 1.8 mm) overlap areas between the coupling and probe beams. This configuration allows to address different groups of atoms within one vapour cell at the same instant of time. The transmission signal of the probe beams is collected by a lens and focused onto a photodetector. For the purpose of retrieving the frequency and amplitude of the modulation signal the photodetector is connected to a spectrum analyser.  

For the frequency stabilisation of the probe and coupling lasers, two auxiliary Rb vapour cells are employed. The probe laser is stabilized to a saturated absorption spectroscopy signal of the \(^{87}\text{Rb} \text{D}_2\)-line. With the AOM in front of the experimental cell, see Fig. 1(a), we obtain four beams with frequencies close to the transition \( 5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3) \). For the stabilisation of the tuneable coupling laser the EIT signal of a \( \mu \)-metal-shielded Rb vapour cell is used, and the laser can be stabilized to different Rydberg levels \( nD_{5/2} \) and \( nD_{3/2} \) with \( n = 30 \) to 70. For the results presented in this paper we use the Rydberg level \( 52D_{5/2} \).  

Our experimental vapour cell is kept at a temperature of 85°C yielding a ground state atom density of \( \sim 10^{12} \text{cm}^{-3} \) for a \(^{87}\text{Rb} \) sample. The two optical fields that are passing through the cell are coupled to the Rydberg level \( 51F_{5/2} \) with a MW carrier field at 16.532 GHz. This field is generated by an analog signal generator that feeds a 10 dBm signal into a home-built helical end-fire antenna. In axial mode the antenna radiates microwave fields along the helical axis and the radiation is circularly polarized. The antenna is located 30 cm from the vapour cell. With increasing field strength of the MW field, the amplitude of the EIT signal decreases while its width broadens and for MW electric fields >10 dBm our transmission signal splits into two AT peaks.

The MW carrier field is further amplitude modulated with a sinusoidal signal with frequencies between 100 kHz and 1 MHz. This results in a variation of the transmission of the probe fields, which can be directly measured with the combination of photodetector and spectrum analyser and permits to retrieve the initial AM signal.

III. RESULTS

A. SNR and Bandwidth of a Single Receiver

Figure 2(a) shows the demodulated probe signal for a 200 kHz amplitude modulated carrier field, measured with the spectrum analyser for a resolution bandwidth of 3 kHz. The transmitted probe field is detected by...
the modulation frequency to the noise floor on the spectrum analyser at the respective frequency in absence of the modulation. As can be seen from Fig. 2(a), the signal height and with it the SNR_{dB} grow with increasing probe power in the presented scenario (black to red).

The development in SNR_{dB} as a function of probe power is shown in more detail in Fig. 2(b). Initially, the SNR_{dB} grows with increasing probe power, but saturates at ~ 150 µW, and slowly decreases for even higher probe powers. The growth of the SNR_{dB} with probe power is related to an increase in peak contrast, as illustrated in Fig. 2(c), which is the difference between the probe transmissions at the EIT peak in presence and absence of the carrier RF field. In the four level scheme in Fig. 1(b), the applied RF field suppresses the EIT transmission on resonance as shown as dotted lines in Fig. 2(c) for two different probe Rabi frequencies (black and blue). For strong RF fields the EIT transmission on resonance is suppressed and can reach the baseline, which is given by the absorption of the probe beam without RF and coupling field. The development of peak contrast with probe power (∝ Ω_p^2) can be qualitatively explained as follows: For larger Ω_p, power broadening leads to an increase of the spectral width of the atomic absorption line, resulting in an increased transmission of the probe beam and a rising baseline transmission. At the same time, for a fixed Rabi frequency of the coupling field, Ω_c, and weak Ω_p the population of the meta-stable Rydberg state increases with Ω_p, since the population ratio between the ground and Rydberg state is determined by Ω_p^2/Ω_c^2. If less atoms are in the ground state the transmission of the probe field increases. Overall this results in a larger EIT peak [21], and the observed initial rise of the SNR_{dB} in Fig. 2(b). For even larger Ω_p the EIT peak transmission saturates [22] while the two-level baseline transmission continues to grow, see Fig. 2(c), explaining the saturation and slow fall off of the SNR_{dB}. Moreover, in our setup the noise floor on the spectrum analyser rises as quadratic function of the probe power for > 50 µW, see Fig. 7 in the Appendix A, and limits the achievable SNR_{dB}. The dominant mode of noise in our experiment is introduced by an AOM which is far above that posed by photon shot noise (more discussed in Appendix A).

In addition to the probe power, the SNR_{dB} depends on the modulation frequency of the carrier RF field, as shown in Figure 3(a). The fall-off of the SNR_{dB} with increasing AM frequency sets the bandwidth of the receiver system. We define the BW limit as the cutoff point with SNR_{dB} = 10 dB. Figure 3(a) shows a measurement of the BW for a single probe beam and five different probe powers. For faster modulations the SNR_{dB} decreases and reaches its BW limit at 380 kHz for probe powers ≥ 100 µW. The slope of the curves is determined by atomic parameters such as decoherence rates set by Doppler broadening and transit times, which are the same for all curves in Fig. 3(a). Increasing the SNR_{dB} initially improves the cut-off frequency, but as the SNR_{dB} saturates the BW saturates as well.
Figure 3. (a) SNR_{dB} as a function of AM frequency of the carrier MW field for different power levels of a single probe beam. The plot shows average values of four probe beams with frequency offsets to the resonance of $-4.5$ MHz, $-1.5$ MHz, $1.5$ MHz and $5.5$ MHz. The cubic fit curves are to guide the eyes. (b) SNR_{dB} as a function of AM frequency for combinations of up to four probe beams of $25$ µW with frequency offsets to the resonance frequency of $f_1 = -4.5$ MHz, $f_2 = -1.5$ MHz, $f_3 = 1.5$ MHz and $f_4 = 5.5$ MHz. Measurements were taken for all combinations of $f_1, f_2, f_3, f_4$ and average values and corresponding standard deviations are presented.

B. Multiple Atomic Receivers

To overcome the constraints in SNR_{dB} and BW described in Sec. III A we distribute the power of our single probe beam over multiple probe beams. In combination with a single coupling beam we obtain independent detection volumes within our vapour cell. We use AOM driving frequencies with $\Delta f = 3 - 4$ MHz between adjacent beams and observe a spatial separation of $\sim 100$ µm in the focal plane, see Fig. 1(c). By this means we obtain a single-input-multi-output (SIMO) configuration, as it is used in the context of smart antenna technology for improved wireless communication performance. Adding multiple antennas at both the transmitter and receiver has proven to offer significant increases in data throughput [23]. Figure 3(b) shows the SNR_{dB} versus AM frequency for one, two, three and four probe beams with individual powers of $25$ µW at their probe frequencies $f_1$ to $f_4$. The SNR_{dB} drops towards higher AM frequency, similar to the scenario for a single receiver in Fig. 3(a), since the slope of the curves is determined by the atomic parameters of our experimental setup. Crucially, however, the saturation of the SNR_{dB} for a single beam can be avoided. This allows us to exceed the BW limit of the single beam setup, as shown in Fig. 4. While for two beams the BW limit approximately matches the scenario of a single beam with twice the power, a clear improvement in BW appears for $N \geq 3$, where $N$ is the number of beams. The saturation in SNR_{dB} for the single beam setup for probe powers $> 75$ µW can be avoided. For three and four beams the BW limit is extended to $\sim 480$ kHz and $\sim 560$ kHz respectively, exceeding the maximum bandwidth of $\sim 380$ kHz of a single beam.

Assuming that two receiver areas are independent and have identical parameters such as $\Omega_p$, $\Omega_c$, beam frequencies, waists, and atomic densities, the signal amplitude increases by a factor of two. We note that doubling the optical power that contributes to the signal increases the SNR_{dB} by a factor of 4 (roughly 6 dB), as e.g. found in Fig. 3(a) (black to blue line). This is because the optical power $P_{op}$ hitting the photodetector translates into a voltage $V \propto P_{op}$, and the spectrum analyser measures the corresponding electric power $P_{el}$, for which $P_{el} \propto V^2$.

In Fig. 4(a) we show the increase in BW for up to four beams. As expected (see Appendix B) the BW scales logarithmically (black line). For the single receiver the bandwidth saturates around $\sim 380$ kHz (blue shaded area). In the context of Rydberg receivers the achievable data capacity for $N$ receiver volumes at a given amplitude modulation frequency $f_{AM}$ is given by Eq. (2) as

$$C_A(N) = f_{AM} \times \log_2(1 + N^2 \times \text{SNR}_{N=1}).$$ (3)

Figure 4(b) presents the data capacity for three different modulation frequencies and up to four beams. The data capacity shows significant enhancement, following the predicted behaviour of Eq. (3) (dashed lines). Moreover the data capacity depends on the amplitude modula-
Figure 4. (a) 10 dB bandwidth limit of a single probe beam as function of the probe power (blue) and for multiple beams (red), where the probe power is distributed equally among \( N \) beams. The BW increases with logarithmically (black line), and surpasses the BW limit of the single beam (shaded area). (b) Data capacity for three different AM frequencies and up to four probe beams. The dashed lines show the scaling of Eq. (3). (c) Data capacity versus amplitude modulation frequency for \( N \) beams.

C. Characterisation of the Distributed Receivers Setup

1. Deviations of EIT peak heights for different receiver volumes

Unlike in an idealized scenario with identical distributed receivers, in our experimental setup the receiver volumes differ slightly due to the geometry of the setup and since the probe power is distributed via an AOM. Therefore, we show average values of all four probe beam combinations in Figs. 3 and 4. Deviations between the detected SNR_{dB} for different probe frequencies are caused by a change in the EIT condition. The main contribution comes from slightly different beam waists in the overlap area, affecting the ratio \( \Omega_c / \Omega_p \). To illustrate the change of the EIT transmission for different probe frequencies, we present in Fig. 5 the EIT profiles for a scan of the coupling beam frequency. The AOM-offset of the probe frequency with respect to the two-level resonance frequency is denoted as \( \Delta \). For all frequencies we observe two EIT peaks, since the EIT condition can be met for the \( 52D_{5/2} \) and \( 52D_{3/2} \) Rydberg states. Relevant in this investigation is the larger peak. For a fixed probe power of 300 \( \mu \)W the height of the EIT peak changes with \( \Delta \), since the position of the probe beam in the focal plane moves as \( \sim \Delta \times 37 \mu \)m/MHz. Considering the angle between the counter-propagating probe and coupling beam, and a scan of \( \Delta = 40 \) MHz the overlap areas are separated by up to 40 nm, which is approximately twice as large as the Rayleigh lengths of the probe and coupling beam. The appearance of two maxima at \( \Delta = -10.5 \) MHz and \( \Delta = 20.5 \) MHz suggests that the focal plane of probe and coupling beam do not coincide. For the probe frequencies \( f_1 \) to \( f_4 \) of Fig. 3(b) the EIT peak height differs by 10\% for a fixed probe power, which translates to deviations in the SNR_{dB}. This technical limitation can be mitigated, for example by adjusting the probe power of individual beams.

Figure 5. Probe transmission for different AOM driving frequencies \( \Delta \) (EIT resonance at \( \Delta = 0 \)) at a fixed probe power of 300 \( \mu \)W. The coupling laser frequency is scanned and the frequency axis calibrated using the known splittings between the states \( 52D_{5/2} \) (large peaks) and \( 52D_{3/2} \) (smaller peaks on the left side).
2. \textit{SNR}_{dB} for different probe beam frequencies

With the objective to find optimised probe frequencies for our system, the coupling laser was locked to the $5F_{3/2} \leftrightarrow 52D_{5/2}$ transition and the probe frequency swept over a 40 MHz range using the AOM. In difference to the measurements in Fig. 5, we allow for changes in the probe power with AOM driving frequency, which is caused by the dependence of the AOM efficiency on the driving frequency. The \textit{SNR}_{dB} was determined as a function of the AOM frequency (probe frequency) for an amplitude modulated MW field at 100 kHz. The results are presented in Fig. 6(a)-(c) as blue data points. In our frequency scan, we observe two minima ($\Delta = -12$ MHz and $\Delta = 5$ MHz), which can be associated with points for which the EIT transmission does not change in presence of the MW field. High \textit{SNR}_{dB} occurs for the largest change in probe transmission due to the applied MW field. For a symmetric AT profile, as depicted in Fig. 6(d), we expect a symmetric scenario in Fig. 6(a)-(c) with three peaks with a vertical line symmetry at the resonance frequency $\Delta = 0$, and e.g. observed in [15]. A number of factors can lead to the observed asymmetry in Fig. 6(a)-(c). First, with our MW electric field we intend to couple the Rydberg states $52D_{5/2} \leftrightarrow 51F_{7/2}$ which has transition dipole moments up to 2260 a$_0$e. However, a second Rydberg state, $51F_{5/2}$, is located only 1.2 MHz away and can shift the AT-profile. Secondly, the probe frequency is scanned using an AOM with maximised diffraction efficiency at the resonance $\Delta = 0$. Lastly, the EIT peak height decreases rapidly for frequencies $\Delta < -10$ MHz, as shown in Fig. 5, due to weaker overlap of coupling and probe beam. This explains the difference in height of the left and right peak in Fig. 6(a)-(c).

3. Effect of adding a second probe beam

In order to characterise the performance with multiple probe beams, we scanned the frequency of the first probe beam in presence of a second probe beam at three fixed frequencies -3.5 MHz, 8.5 MHz and 15.5 MHz. We measured the \textit{SNR}_{dB} of the two beams by combining the two probe signals on the photodetector. The obtained values of \textit{SNR}_{dB} are presented in red in Fig. 6(a)-(c). One could naively expect the \textit{SNR}_{dB} to remain at least at the value given by the fixed-frequency beam, depicted in Fig. 6(a)-(c) as horizontal black lines. Instead, for two probe beams we predominantly observe a drop in the \textit{SNR}_{dB} if the two probe frequencies are in differently shaded frequency areas (grey and blue), and a rise for two frequencies in identically shaded areas. A descriptive explanation for this phenomenon is given in Fig. 6(d). While the grey and blue areas both show a significant change of the EIT signal in presence of a MW electric field, for grey areas the probe transmission increases in height, whereas the signal drops in the blue area. By detecting both beams on the same photodetector the transmission signals from two beams can be effectively “out of phase”. If both components are equally strong, a zero occurs in the \textit{SNR}_{dB}. Otherwise, the stronger signal dominates the scenario. Hence, for our experimental setup it is crucial to choose frequencies within identically colored areas. All beams can then be detected with a simple detection scheme, involving only a single photodetector. Alternatively, the probe transmission signal can be detected with individual photodetectors to allow for less sensitivity in the choice of probe frequencies. For the \textit{SNR}_{dB} measurements of up to four distributed beams,
we used a separation of $3 - 4 \text{ MHz}$ for adjacent probe beams centered around $\Delta = 0$. With this choice the individual beams have similar SNR$_{\text{dB}}$ levels, as well as spatially separated overlap areas.

We note that the frequency deviations of the probe beams in or setup could be of potential benefit for an atom-based multi-input-multi-output (MIMO) configuration. These configurations use spatial multiplexing and allow for an even larger increase in data capacity proportional to $N$, where $N$ is the number of transmitter and receive antennas. For the generation of multiple probe beams with identical frequencies electromechanically driven mirrors or liquid crystal deflectors could be implemented.

### IV. DISCUSSION

The fastest switching time in an atom-based receiver is given by the contrast of optical transmission and the detection noise. Using purely classical light sources, the noise floor is ultimately limited by the photon shot noise, while the transmission contrast is determined by the lifetime of a single atom in a dark state, the number of participating atoms in the EIT process, and the input probe beam power. The atom-switching time in our realisation is primarily limited by the EIT pumping rate $\Omega_{\text{EIT}} = \Omega^2 / 2 \Gamma$ [20], which describes the time atoms need to re-establish the EIT dark state when the MW field is turned off.

For a given realisation with a particular atom-switching time, one expects that increasing the probe power or the number of the participating atoms within the receiver volume would lead to a larger contrast in optical transmission, and therefore increase the SNR. In this paper we show that the SNR saturates beyond a certain probe power, but by spatially distributing the probe power to address different atoms, one can increase the SNR, which ultimately leads to an increase of the data capacity. Our results demonstrate a scaling of the data capacity with $C_{\text{SIMO}} = \text{BW} \times \log_2(1 + N^2 \times \text{SNR})$ for $N$ probe beams. The capacity advantage of the distributed receiver stems from the reduction of the dephasing processes. These are caused by high atomic densities in the Rydberg state due to a high density of participating atoms and due to high probe beam power.

Our results particularly highlight the challenge of scaling up the data capacity of Rydberg atomic receivers by classical means, such as scaling up the probe volume. To put this in perspective, in order to increase the data capacity by an order of magnitude, one needs to implement more than thirty distributed receivers with the receiver volume larger by the same ratio. Assuming a probe volume of a single receiver to be $\sim 0.3 \text{ mm}^3$, a distributed receiver with a volume of $\sim 1 \text{ cm}^3$ would lead to an increase of the data capacity by a factor of $\sim 10$. This shows the importance of maximising single-channel data capacity by reducing the detection noise floor, or by employing collective effects in atomic excitation/de-excitation. Such collective effects have so far remained elusive in warm atomic vapour, but can be achieved in cold atomic gases [24].

### V. CONCLUSION AND OUTLOOK

We have considered a simple setup employing spatially distributed atomic receivers that allows to surpass the SNR limit of an individual atom-based receiver, resulting in an improved channel capacity. The concept of receiver arrays has proven beneficial in wireless communication systems for high-speed transmission and increased capacity. For example for a SIMO system, as presented in this work, an increase in channel capacity to $C_{\text{SIMO}} = \text{BW} \times \log_2(1 + N^2 \times \text{SNR})$ [19] for $N$ receiving antennas has been derived. We experimentally confirmed the same scaling for the channel capacity of our atomic-receiver system with $N$ probe beams (receiver volumes). Moreover, we observed a significant increase in SNR$_{\text{dB}}$, and BW – the latter scaling logarithmically for our Rydberg atom-based RF-to-optical receiver. We showed that such enhancement of the BW cannot be obtained by a single receiver with a similar level of combined optical power due to the saturation of the power signal to noise ratio. Our approach benefits from the little additional resource overhead needed to add multiple probe beams, if generated by the first order of an AOM and a multi-tone frequency source. While the results shown in this work were carried out with $N \leq 4$ probe beams, the number of beams can easily be expanded [25]. Extending the system with additional transmitter RF antennas in a configuration where the receivers can distinguish between the transmitter will allow one to realise a multi-in-
multi-out (MIMO) system, promising further enhancement in channel capacity. For an additional transmitter antenna, we expect an improvement in channel capacity by $2 \times \log_2(1 + N^2 \times \text{SNR})$. This however requires that the spatial separation between the distributed atomic receivers to be in the order of the RF wavelength [23].

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Appendix A: Noise assessment of the AOM

The key component for the generation of multiple probe beams in our experimental setup is a continuously running AOM, see Fig. 1(a). This AOM is the main source for noise, degrading our SNR$_{\text{dB}}$ measurements. In general, two sources of noise can be induced by an
AOM: phase noise from the AOM driver and RF amplifier, and intensity noise. The intensity noise, which originates from relative diffraction efficiency fluctuations (RDEF) [26], dominates in our setup. A measurement of the noise power on the spectrum analyser over a range of 50 to 250 kHz with a resolution bandwidth of 3 kHz and for different probe beam powers is shown in Fig. 7(a). The red data points represent a measurement in which the first order of the AOM (∼65% efficiency) was detected on the photodetector (Thorlabs PDA 100A-EC, bandwith up to 2.4 MHz) and the optical power incident on the AOM was varied. We find that the noise power scales as quadratic function of the probe power. In a consecutive measurement (blue) the AOM was removed from the beam path, resulting in a linear increase of noise power with increasing probe power. A shot noise limited scenario (3 dB gain above the detector noise floor) is reached for probe powers > 4 mW.

The intensity noise of the AOM limits the achievable SNR_{dB} as depicted in Fig. 7(b) (blue points). Towards higher probe powers the peak height of the AM signal, see Fig. 2(a), saturates while the noise floor increases quadratically with the probe power, resulting in a fall-off of the SNR_{dB}. If we compensate for the increasing noise floor and only consider shot noise (black points) the SNR_{dB} saturates at ∼32 dB, and overall a higher SNR_{dB} can be obtained. In order to reduce the intensity noise of the AOM the RF driving power of the AOM can be set close to its saturation point. To further reduce the noise, alternative options to generate multiple beams can be employed, as discussed in Sec. III C 3. For a photon-shot-noise-limited measurement an optical heterodyne detection scheme can be employed, where a local oscillator beam is mixed with the transmitted probe as e.g. used in [20].

**Appendix B: BW and data capacity for multiple receivers**

For a SIMO configuration with N identical receiver volumes (i.e. N probe beams) the signal-to-noise ratio in decibel is given by by

$$\text{SNR}_{dB}(N) = \text{SNR}_{dB,N=1} + 20 \times \log_{10}(N).$$  \hspace{1cm} (B1)

This relates to an improvement of bandwidth with N as

$$\text{BW}(N) = \text{BW}_{N=1} + 20/m \times \log_{10}(N),$$  \hspace{1cm} (B2)

where m is the slope defined by the falloff of the curves towards higher AM frequencies in Figs. 3(a)-(b). The slope, m, depends on atomic parameters, such as coherence rates and vary for different experimental setups.

The achievable communication rate for a channel at a given amplitude modulation frequency $f_{AM}$ is given by the Shannon-Hartley theorem, Eq. (1), as $C = f_{AM} \times \log_{2}(1 + \text{SNR}).$ Equation (B1) can be used to derive the theoretical data capacity for N receiver volumes

$$C_{A}(N) = f_{AM} \times \log_{2}[1 + \text{SNR}(N)]$$
$$= f_{AM} \times \log_{2}[1 + 10^{\text{SNR}_{dB}(N)/10}]$$ \hspace{1cm} (B3)

$$\approx f_{AM} \times \log_{2}[1 + N^2 \times \text{SNR}_{N=1}],$$

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