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Opportunities to search for extraterrestrial intelligence with the FAST

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Abstract The discovery of ubiquitous habitable extrasolar planets, combined with revolutionary advances in instrumentation and observational capabilities, has ushered in a renaissance in the search for extraterrestrial intelligence (SETI). Large scale SETI activities are now underway at numerous international facilities. The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single-aperture radio telescope in the world, and is well positioned to conduct sensitive searches for radio emission indicative of exo-intelligence. SETI is one of the five key science goals specified in the original FAST project plan. A collaboration with the *Breakthrough Listen Initiative* was initiated in 2016 with a joint statement signed both by Dr. Jun Yan, the then director of National Astronomical Observatories, Chinese Academy of Sciences (NAOC), and Dr. Peter Worden, Chairman of the Breakthrough Prize Foundation. In this paper, we highlight some of the unique features of FAST that will allow for novel SETI observations. We identify and describe three different signal types indicative of a technological source, namely, narrow band, wide-band artificially dispersed and modulated signals. Here, we propose observations with FAST to achieve sensitivities never before explored. For nearby exoplanets, such as *TESS* targets, FAST will be sensitive to an EIRP of 1.9×10^{11} W, well within the reach of current human technology. For the Andromeda Galaxy, FAST will be able to detect any Kardashev type II or more advanced civilization there.

Key words: Search for Extraterrestrial Intelligence — Five-hundred-meter Aperture Spherical radio Telescope

1 INTRODUCTION

The search for life beyond Earth seeks to answer one of the most profound questions regarding human beings' place in the universe − Are we alone? Recent discoveries of thousands of exoplanets, including many Earth-like planets (Howell et al. 2014; Dressing & Charbonneau 2015), have generated abundant targets of interest. It is possible that some fraction of these planets host life sufficiently advanced to be capable of communicating via electromagnetic waves. Coherent radio emission is commonly produced by our technology for various applications. Moreover, radio waves are also energetically cheap to produce and can convey information at maximum speed across large interstellar distances. Cocconi & Morrison (1959) speculated that frequencies near 1420 MHz (the hydrogen line) are particularly well suited for interstellar communication. Later it was suggested that frequencies between the hyperfine hydrogen transition and the Λ-doubling OH lines (1400 MHz $\sim$ 1700 MHz) could be considered a "cosmic water-hole" (Oliver & Billingham 1971), where intelligent species might transmit a deliberate beacon to other technologically advanced species[1].

Radio astronomy has long played a prominent role in the search for extraterrestrial intelligence (SETI). Large single dish radio telescopes, with their enormous collecting area, flexibility of operation and large beams relative to interferometers, are ideal for both targeted and large-area SETI surveys. Drake (1961) conducted some of the earliest SETI experiments near 1420 MHz towards two stars using the National Radio Astronomy Observatory's (NRAO) 26-meter radio antenna. Other radio telescopes such as the Arecibo radio telescope (Arecibo), Parkes radio telescope (Parkes), and NRAO's 91-meter, 300-foot and 140-foot dishes have also been employed for SETI experiments (Horowitz & Sagan 1993; Horowitz et al. 1986; Tarter et al. 1980; Verschuur 1973). Most of these early studies were limited to only a few stars. One of the largest SETI experiments of the 20th century, *Project Phoenix*, was conducted from the Arecibo, Parkes and NRAO's 43-m telescopes, and surveyed around 1000 nearby stars (Tarter 1996; Dreher 1998; Backus 1998; Cullers 2000; Backus & Team 2002). Later studies by Siemion et al. (2013) utilized the 100-meter Robert C. Byrd Green Bank Radio Telescope (*hereafter* GBT) for a targeted search towards 86 stars in the *Kepler* field. Most recently, Enriquez et al. (2017) published the most comprehensive targeted radio SETI survey of 692 nearby stars, also using the GBT. It should be noted that, in congregate, all the several dozen significant radio SETI sources, spanning the last six decades, have explored only a fraction of the multidimensional parameter space of potential signals (Tarter 2003; Wright et al. 2018).

The *Breakthrough Listen Initiative* (BLI) is a US $100 M 10−year effort to conduct the most sensitive, comprehensive and intensive search for advanced life on other worlds (Worden et al. 2017; Isaacson et al. 2017). BLI is currently utilizing dedicated time on three telescopes, including the GBT (MacMahon et al. 2018) and Parkes (Price et al. 2018) operating at radio wavelengths and the optical *Automated Planet Finder* (Lipman et al. 2019). The BLI team has leveraged both standard and bespoke tools to construct a flexible software stack to search data from these and other facilities for signals of interest.

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single aperture radio telescope in the world (Nan 2006; Nan et al. 2011; Li & Pan 2016). With the newly cryogenically-cooled FAST L-band Array of 19-beams (FLAN: Li et al. 2018), FAST is poised to become one of the most sensitive and efficient instruments for radio SETI experiments. Since the early days of its conception, Nan et al. (2000) and Peng et al. (2000) indicated that FAST will be a leading facility to search for signals from extraterrestrial intelligence (ETI). Nan et al. (2000) also highlighted that a dedicated SETI survey with FAST will be 2.5 times more sensitive and will be able to cover five times more stars than the aforementioned *Project Phoenix*. FAST surveys will be complimentary to sensitive SETI experiments being carried out by BLI. In 2016, BLI signed a Memorandum of Understanding with the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) for future collaboration with FAST.

Here, we outline novel SETI experiments possible with FAST and quantify their expected outcomes based on test observations. Section 3 highlights two targeted SETI experiments, namely, a survey of nearby galaxies and nearby stars with newly-discovered exoplanets. In order to conduct these surveys, a dedicated instrument is required which can capture baseband raw voltages to acquire the data products for various signal searches. The *Breakthrough Listen* team has developed tools to capture baseband voltages into the Green Bank Ultimate Pulsar Processing Instrument (GUPPI[2]) raw format and then con-

[1] We note that our implicit definition of advanced species only considers civilizations who have developed radio communication capabilities.

[2] The GUPPI support guide can be found @ `https://safe.nrao.edu/wiki/bin/view/CICADA/GUPPISupportGuide`

vert them to the various spectral and temporal resolutions during the offline processing (MacMahon et al. 2018; Lebofsky et al. 2019). More details about this backend are also addressed in Section 2. Section 3 quantifies FAST SETI's potential among two distinctive groups of targets, namely, nearby *Transiting Exoplanet Survey Satellite* (*TESS*) planets and the Andromeda galaxy. In Section 4, we discuss three potential signal types, which are likely to provide a new window for radio SETI experiments. In Section 5, we estimate the sensitivities of these FAST SETI surveys. We also describe a FAST experiment which can, with just a few hours of observing, potentially place the most stringent limits on the presence of artificial transmitters within its operable frequency range. A brief summary is provided in Section 6.

2 FAST SETI SYSTEM

FAST has an active, segmented primary surface of 500 meters in diameter, with a maximum effective aperture of 300 meters. The receiver cabin is driven by six cables connected to mechanical drives through six towers. Pointing and tracking can be accomplished by reshaping the primary surface and maneuvering the focal cabin on the curved aperture plane. Such a concept provides access to a much larger region of the sky (-14° to $+66^\circ$ in declination) compared to Arecibo (Li et al. 2018). The FLAN is the largest of its kind, compared to the seven beams of Arecibo and 13 beams of Parkes, which provides both unprecedented survey speed and efficiency in discriminating radio frequency interference (RFI) for SETI. FLAN has a $T_{\rm sys}$ between 18–24 K, which, combined with the effective aperture, amounts to a gain of 16 K Jy^{-1}, and will enable 2.5 times more sensitive SETI surveys than Arecibo (10 K Jy^{-1} gain and 30 K $T_{\rm sys}$)[3] at similar frequencies.

As one of the major FAST surveys, the Commensal Radio Astronomy FAST Survey (CRAFTS, Li et al. (2018)) will utilize FAST's 19-beam receiver to conduct searches for pulsars and HI galaxies, HI imaging and fast radio bursts (FRBs). An additional backend, namely named *FAST-SetiBurst* (Fig. 1), has been installed for a commensal SETI – which can record thresholded spectra – focusing on narrow-band signals. This instrument is similar in design and operation to the seven beam backend at Arecibo (Chennamangalam et al. 2017). The SETI section of the *FAST-SetiBurst* instrument consists of 38 ultra-high resolution FPGA/GPU based spectrometers for each of the 19 beams of the multibeam receiver (for both polarizations). Each of the 250 million channel spectrometers has a 4 Hz spectral resolution and covers a 450 MHz band, from 1025 to 1475 MHz. The spectrometers search in real-time for narrow-band signals and output files that contain a list of narrow-band signals with their frequency, Julian time, power, position in the sky as well as other meta information. The *FAST-SetiBurst* instrument also continuously records raw voltage streams from all 19 beams and both polarizations (38 signals at 500 MHz bandwidth, each totaling 38 billion samples per second). This instrument and associated software are open source and available for use by all FAST observers for SETI and FRB science related projects. A more detailed description of this FAST specific backend can be found in Zhang et al. (2020).

It should be noted that FAST-SetiBurst cannot do a coherent search for drifting narrow-band signals as it only stores thresholded spectra. Moreover, for more complicated classes of signal searches, baseband raw-voltages are required to be utilized and coherent searches need to be performed. Section 4 outlines some of these searches that are possible to carry out if raw-voltages can be acquired and processed. Figure 1 also displays a prospective GPU equipped compute nodes that can be connected to the existing multicast switch network to capture coarsely channelized baseband raw-voltage spectra from ROACH-2[4] boards and convert them to GUPPI formatted raw-voltages for offline processing. The *Breakthrough Listen* team has deployed such computing clusters at the GBT (MacMahon et al. 2018) and Parkes (Price et al. 2018). We refer readers to these references for further details on the architecture of such a computing cluster.

To demonstrate capabilities of the FAST telescope for SETI, we conducted preliminary observations with the *FAST-SetiBurst* with five minute tracking observations toward GJ 273 b on 2019 September 10. GJ 273 b is one of the closest Earth-sized planets inside the habitable zone of an M-dwarf star (Tuomi et al. 2019), making it one of the most interesting targets for deep dedicated SETI experiments. The preliminary result from the FAST-SetiBurst backend is depicted in Figure 2. The data were taken with 4 Hz channel width, 0.25 s integration time and processed with a threshold cutoff in signal-to-noise ratio (SNR) of 30. The noise level is consistent with the expectation from the radiometer equation for a system of 20 K and effective gain of 16 K Jy^{-1}. As these are thresholded spectra, they cannot be added for the entire length observing duration like in the case of Enriquez et al. (2017). Thus, with $t_{\rm obs}$

[3] `http://www.naic.edu/\%7Eastro/RXstatus/rcvrtabz.shtml`

[4] `https://casper.ssl.berkeley.edu/wiki/ROACH-2_Revision_2`

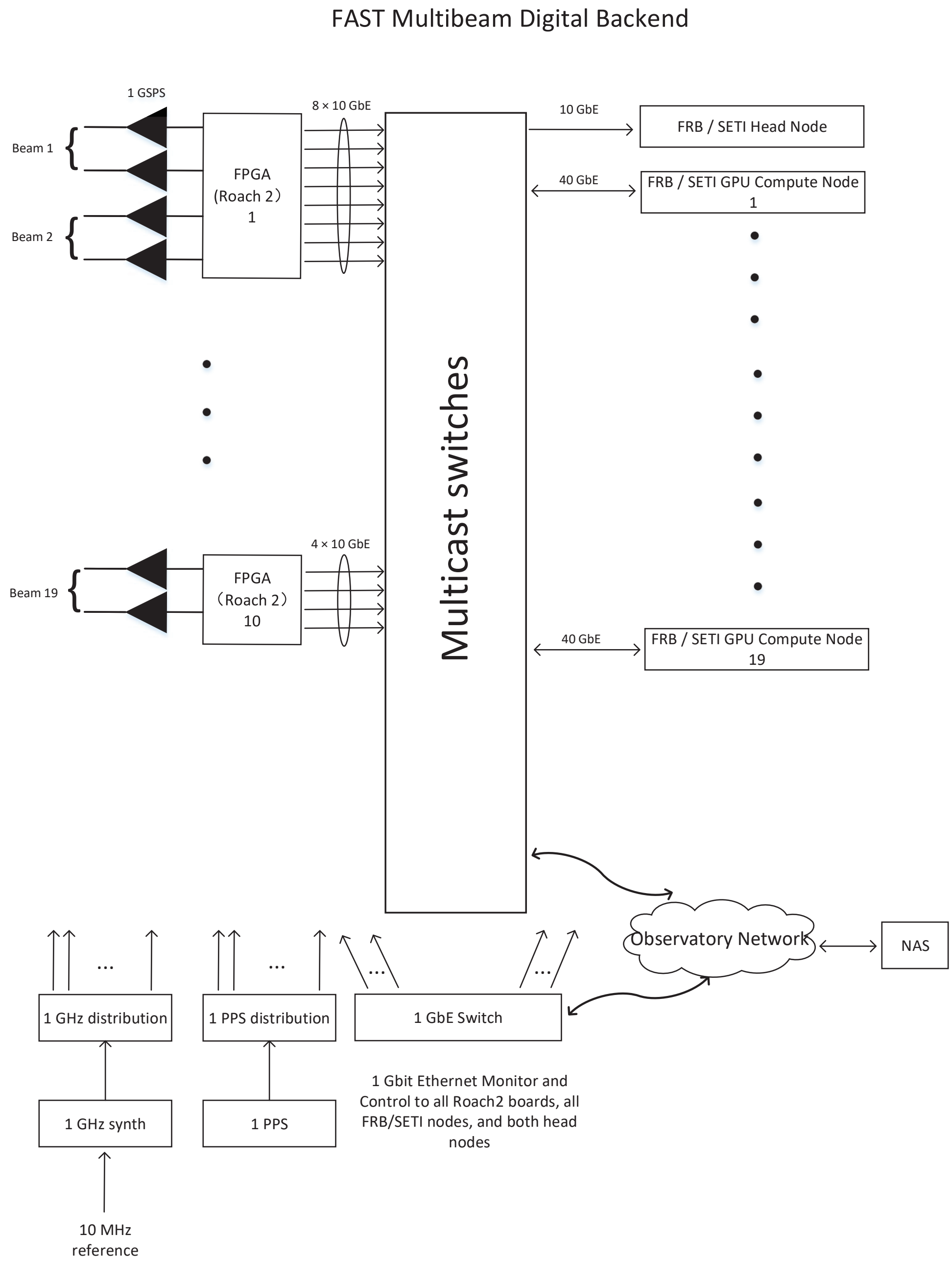

Fig. 1 The schematic diagram of the FAST multibeam digital backend for the FLAN. Note that the radio frequency (RF) signals transmitted over fibers from the focal cabin are digitized simultaneously, which allows for a potential correlation between beams. There are other multiple observatory based backends already installed with the multicast switches, represented with *solid lines*. One possible configuration for connecting a dedicated computer cluster in collaboration with the *Breakthrough Listen* team is signified with *dotted boxes*. This computing cluster could consist of one headnode utilized for system monitoring and metadata collection, 19-compute nodes with GPUs for recording and offline processing, and a dedicated switch for interconnectivity between these compute nodes.

of 0.25 seconds, for GJ 273 b located at 12 light years, the estimated effective isotropic radiated power (EIRP) limit is around 7×10^{10} W.

3 SETI SURVEYS WITH FAST

Kardashev (1964) proposed a classification scheme for technological civilizations based on their energy utilization capabilities. A Kardashev Type I civilization is defined as one that can harness all the stellar energy falling on their planet (around 10^{17} W for an Earth-like planet around a Sun-like star) and a Type II civilization as one that can harness the entirety of the energy produced by their star (around 10^{26} W for the Sun). The Kardashev Type III case would be capable of harnessing all the energy produced by

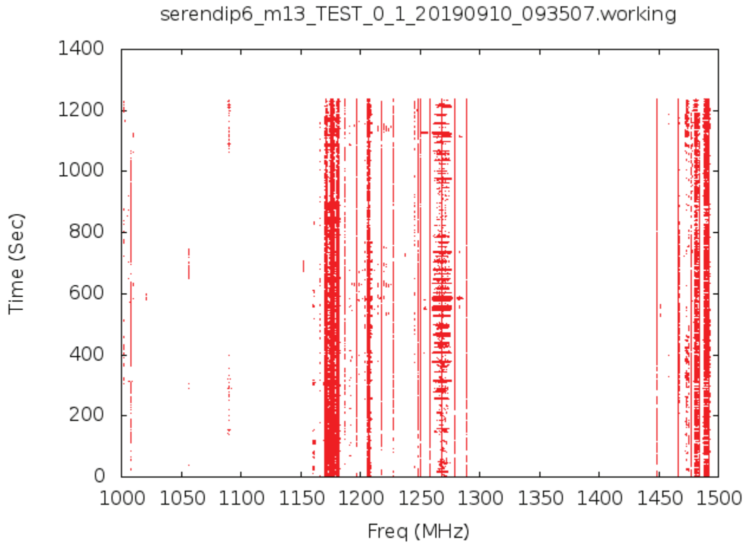

Fig. 2 The "waterfall-plot" is the preliminary result using the *FAST-SetiBurst* backend. The *red points* in the figure represent signals with SNR greater than 30 that have been extracted by the pipeline, containing mostly narrow-band and broad-band RFI. We identify a relatively clean window between 1300–1450 MHz.

all the stars in a galaxy, around 10^{36} W for a Milky Way-like galaxy. The likelihood of the existence of such civilizations among a given number of stars might be sparse, thus, a comprehensive search for Type II and Type III civilizations should be conducted towards a large number of stars. We thus quantify the expected performance of two FAST SETI surveys in terms of Kardashev types, namely a deep blind search toward the Andromeda Galaxy and a targeted search toward *TESS* stars with exoplanets.

3.1 Andromeda System (M31) with FLAN

Nearby galaxies such as Andromeda (M31) and M33 are ideal targets for SETI surveys aiming for very advanced civilizations. Radio interferometers, such as the Very Large Array (VLA) and MeerKAT, provide decent sensitivity and a spatially dynamic range for wide-field SETI observations towards such nearby galaxies. The data rates of such interferometric surveys, however, will remain extremely challenging for the near future[5]. For example, the recent VLA SETI experiments by Gray & Mooley (2017) towards M31 and M33 were limited to a very small spectral window ($\sim$1 MHz) around 1420 MHz. Centered around 1250 MHz, the FLAN provides unprecedented sensitivity over a 400 MHz bandwidth. Figure 3 highlights the FLAN's tiling scheme, which forms a hexagon of about 26′ across with four pointings and covers the entire Andromeda Galaxy with 21 such hexagons. A dedicated FAST SETI survey of M31 with 10 minutes per pointing (see Table 1 and Sect. 5 for sensitivity discussion) will be able to identify any continuous and isotropic transmitters from Type II and Type III civilizations among one trillion stars in the Andromeda Galaxy.

3.2 Surveying *TESS* Stars Across 70 MHz to 3 GHz

Over the last two decades, more than 3000 exoplanets have been discovered, among which several dozen have been confirmed to be inside the putative habitable zone[6]. According to recent estimates, the average number of planets per star is greater than one (Zink et al. 2019). *TESS* was launched in April of 2018 and first surveyed the southern sky before turning to the northern sky in the summer of 2019. *TESS* fully covers its $24^\circ \times 96^\circ$ field-of-view every 30 minutes, while measuring 200 000 bright stars on a two minute cadence in search of Earth-sized planets. Such a large field of view allows for 80% coverage of the entire sky in its first two years (Stassun et al. 2018). Pre-flight estimates of the planet yield suggest that *TESS* will find 1250 planets, 250 of which are at most twice the size of Earth around likely bright dwarf stars. As many as 10 000 planets could be identified in full-frame images around fainter stars (Barclay et al. 2018). These stars are less likely to have been studied with deep observations in earlier SETI

[5] The *Breakthrough Listen Initiative* is in the process of deploying a state-of-the-art 128-node computing cluster at MeerKAT, which will be one of the largest backends ever deployed for radio astronomy, to mitigate these challenges.

[6] `www.phl.upr.edu/projects/habitable-exoplanets-catalog`

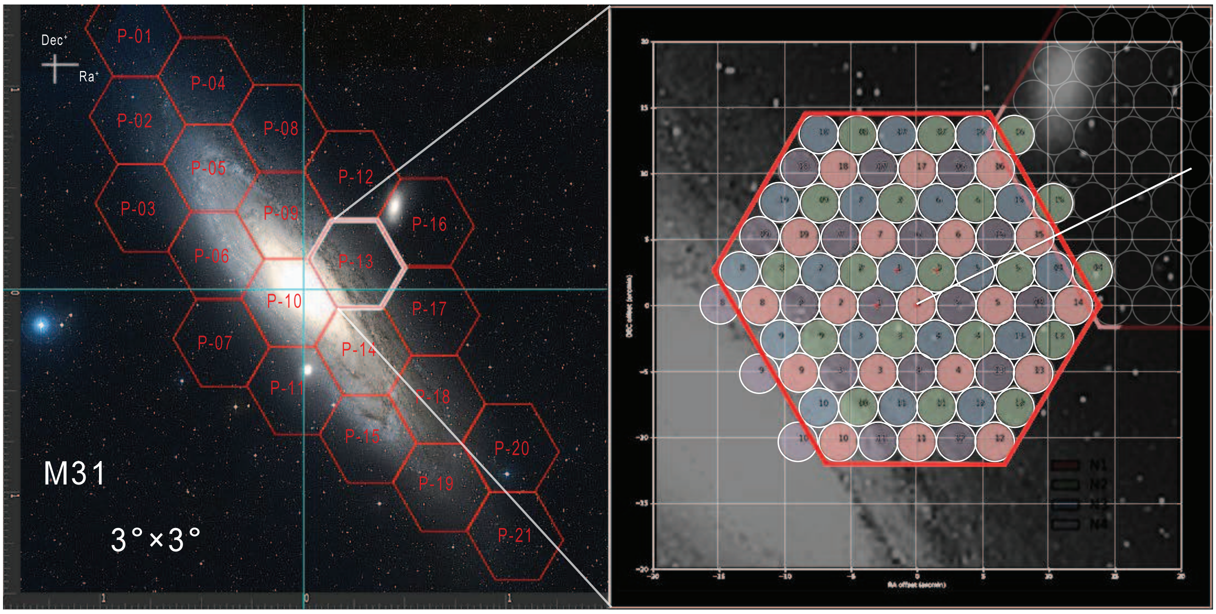

Fig. 3 Proposed RFI-resistant SETI towards the Andromeda Galaxy applying the FAST 19-beam receiver, surveying one trillion s-tars. The right panel showcases four pointings filling a hexagon, with each pointing drawn in a different color. A total of 21 such hexagon tiles are required to cover the Andromeda Galaxy. The image file was taken from *Digitized Sky Survey* archival data (*https://archive.eso.org/dss/dss*).

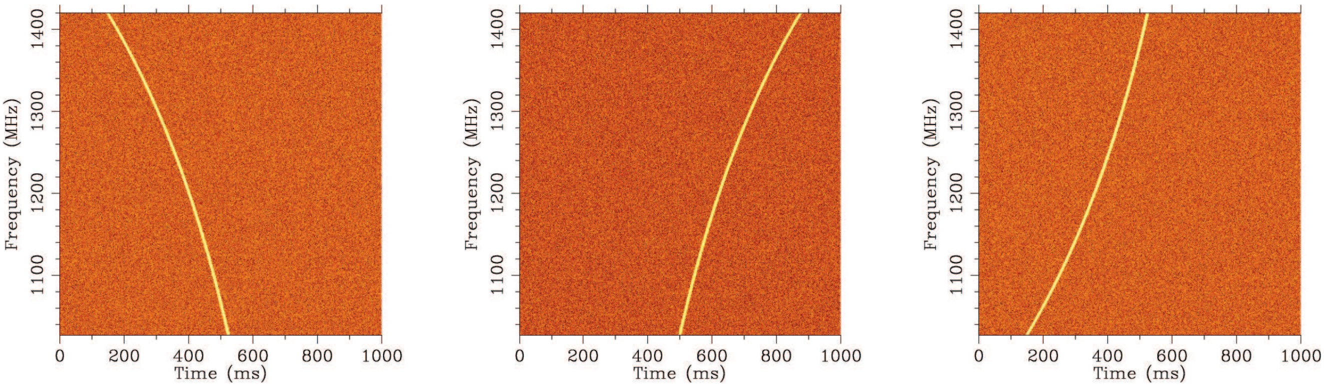

Fig. 4 Three negatively-dispersed simulated pulses. The newly developed pipeline which utilizes ML techniques will be capable of searching for these types of dispersed pulses which the standard transient technique is unlikely to investigate.

Table 1 A Collection of Receivers Expected to be Available with FAST

Receiver Name	RF Band (MHz)	Number of beams	Polarization	T_{sys} (K)	EIRP limits (W)
A1	70–140	1	Circular	1000	9.5×10^{12}
A2	140–280	1	Circular	400	3.8×10^{12}
A3	560–1120	1	Circular	150	1.4×10^{12}
A4	1100–1900	1	Circular	60	5.7×10^{11}
FLAN	1050–1450	19	Linear	20	1.9×10^{11}
A5	2000–3000	1	Circular	25	2.4×10^{11}

EIRP limits are calculated for putative 1 Hz bandwidth signals at a distance of 200 light years observed with 5 minute integration (see Sect. 5). The T_{sys} values are taken from Nan et al. (2011).

experiments. Thus, many of them will be ideal targets for a dedicated SETI project with FAST.

We expect to use all receivers listed in Table 1 (A1, A2, A3, A4 and A5) from 70 MHz to 3 GHz to conduct a deep and comprehensive search towards a subset of stars with exoplanet systems discovered by *TESS*. As indicated in Table 1, such a survey would provide some of the most constraining limits (see Sect. 5) on possible narrow-band transmission yet achieved in radio SETI. It should be noted that although these limits are calculated for narrow-band signals, the proposed observations would provide correspondingly robust limits for other signal types.

4 SIGNAL SEARCHES

4.1 Narrow-band Signals

Narrow-band ($\sim$ Hz) radio signals are one of the most common signal types aimed for by radio SETI. Ubiquitous in early terrestrial communication systems, such signals can be produced with relatively low energy and traverse the interstellar medium easily. They can be readily distinguished from natural astrophysical sources. These signals could either be transmitted intentionally or arise as leakage from extrasolar technologies. The apparent frequency of a distant narrow-band transmitter is expected to exhibit Doppler drift due to the relative motion between the transmitter and receiver. For a radio signal transmitted at rest relative to the Earth's barycenter at frequency ν_0, the Doppler drift rate can be expressed as

$$\dot{\nu}_{\rm Doppler} = \frac{\omega^2 R \nu_0}{c} \ , \tag{1}$$

where ω is the angular velocity, R is the radius of Earth and c is the speed of light. For a transmitter operating at 1400 MHz, the frequency drift rate is $\sim$0.14 Hz s^{-1}. While the motion of the Earth is well known and can be exactly removed, the intrinsic or rotational/orbital drift of an arbitrary extraterrestrial transmitter is unknown, and thus Doppler drift represents a search parameter for narrow-band SETI. In a common data dumping time, say 1 s, the implied Doppler drift will be much smaller than the broadening of any known interstellar spectral lines, thus necessitating the fine spectral resolution of SETI.

FAST is collaborating with the *Breakthrough Listen* group, who has developed an efficient narrow-band search software package which includes a search for such drifting signals, named *turbo*SETI[7]. For the proposed SETI campaign with FAST, we will utilize *turbo*SETI to conduct a similar search and candidate selection procedure as described in Enriquez et al. (2017).

4.2 Broad-band Signals and Modulation Classification Applying Machine Learning

Traditionally, radio SETI has focused on searches for narrow-band signals. In this section, we highlight some of the newly-developed tools that have as yet not been fully explored for SETI. Along with narrow-band signals, we plan to conduct searches on two different types of broad-band signals: wide-band artificially dispersed pulses and signals exhibiting artificial modulation.

4.2.1 Artificially-dispersed pulses

Astrophysical sources such as pulsars (Hewish et al. 1968), rotating radio transients (McLaughlin et al. 2006) and FRBs (Lorimer et al. 2007) exhibit broad-band pulses that are dispersed due to their propagation through the intervening ionized medium. This dispersion causes the higher-frequency component of the pulse to arrive earlier than the lower-frequency component. FAST has already demonstrated its ability to find such signals by discovering around 70 new pulsars in less than a year, (Qian et al. 2019)[8] including finding a pulsar with interesting emission properties (Zhang et al. 2019). Siemion et al. (2010) speculated on an interesting hypothesis that an advanced civilization might intentionally create a beacon of "pulses" with artificial (nonphysical) dispersion. In addition, they also suggested that the energy requirement for such a signal is relatively similar to the energy required for a persistent narrow-band signal. There have been a few attempts to search for such signals (von Korff 2010; Harp et al. 2018); however, no detailed investigations have been carried out. Figure 4 depicts examples of three different types of artificially-dispersed engineered signals which are clearly distinguishable from naturally-occurring dispersed pulses. The *Breakthrough Listen* team has developed tools to search for these classes of signals (Zhang et al. 2018). With the excellent sensitivity of FAST, the aforementioned targeted searches would be ideal to investigate such signals.

4.2.2 Modulating signals of extraterrestrial origins

Modulation schemes are methods of encoding information onto high-frequency carrier waves, making the transmission of that information more efficient. Most of these methods modulate the amplitude, frequency and/or phase of the carrier wave. Broad-band radio emissions exhibiting such underlying modulation represent a third important class of radio emission indicative of an artificial origin, as we would expect any transmission containing meaningful information to exhibit some form of modulation. Harp et al. (2015) carried out a simple modulation signal search using correlation statistics towards known astrophysical sources such as pulsars, quasars, supernova remnants and masers. In the last few years, great progress in the field of machine learning (ML) has opened up a myriad of new op-

[7] `turboSETI:https://github.com/UCBerkeleySETI/turbo_seti`

[8] `http://crafts.bao.ac.cn/pulsar/`

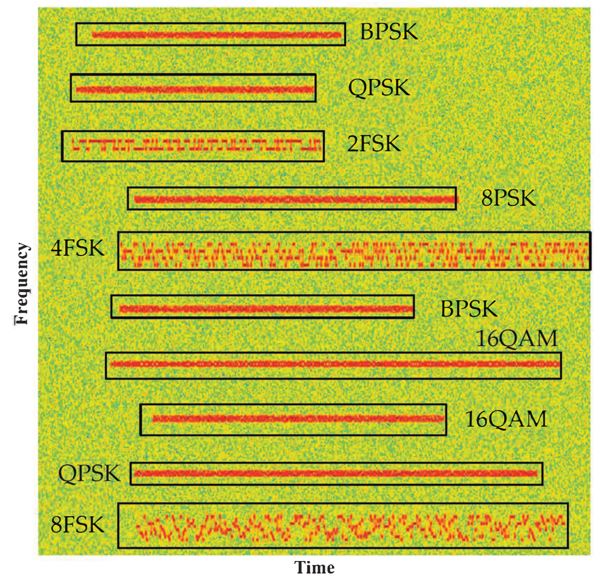

Fig. 5 Example of seven artificially generated modulated signals embedded in a wide radio band. The plot shows observed RF as a function of time in arbitrary units (credit: Zha et al. 2019).

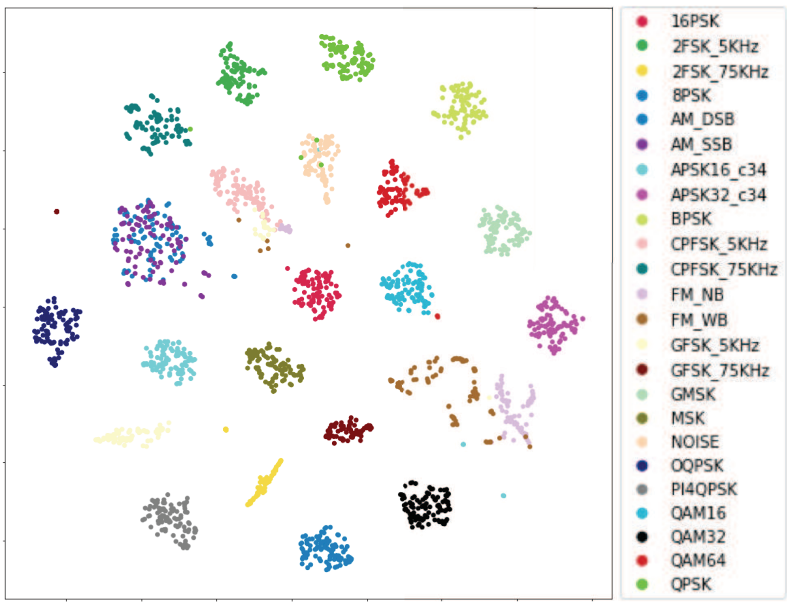

Fig. 6 Application of a modulation classifier developed by the *Breakthrough Listen* team on the simulated radio-frequency data with embedded modulations. The figure displays the t-distributed Stochastic Neighbor Embedding (t-SNE) plot embedding 24 modulations using one of our models. The axes here are arbitrary as they merely represent the space found by t-SNE in which close points in high dimension stay close in the lower dimension. As is apparent, different modulations map to different clusters even in 2-dimensional space indicating that the model does well in extracting features that are specific to the different modulation schemes (Zhang et al. 2020).

portunities in this area. Moreover, Convolutional Neural Network (CNN) classifiers, heavily utilized in computer vision applications, provide advanced capabilities with the aid of high-performance computing. In CNNs, classification of an input signal is carried out through alternating convolution and pooling layers along with a final fully–connected layer providing the desired output classes (see fig. 1 in Albelwi & Mahmood 2017 and references therein). Convolution layers are trained using labeled data of desired classes to extract desired features from a given input signal. After training, the network learns local features to map a given input signal to its closest output class by minimizing a loss function (Albelwi & Mahmood 2017).

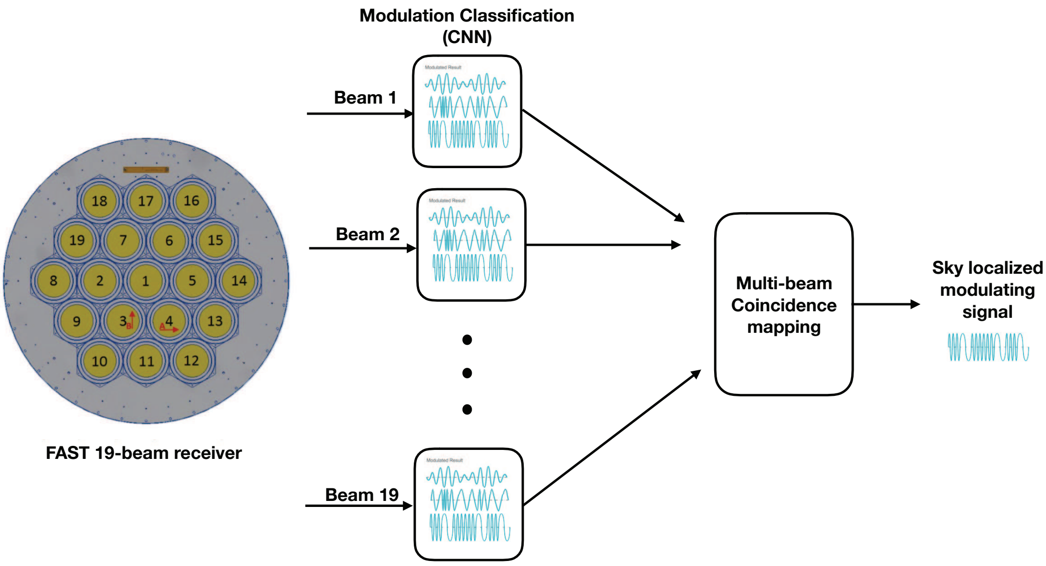

Fig. 7 A schematic of a multi-beam modulation classification and the localizing scheme proposed with the FLAN receiver. The first block represents the standard CNN based modulation pattern identification which can be carried out in each dedicated individual computing node. The second block – running on the headnode or one of the extra compute nodes – receives time-stamp, modulation type, range of signal frequencies and SNR for every candidate from each beam for a multi-beam coincidence mapping. Any signal with sufficient SNR and only found in four nearby beams with similar characteristics can be considered a sky localized candidate.

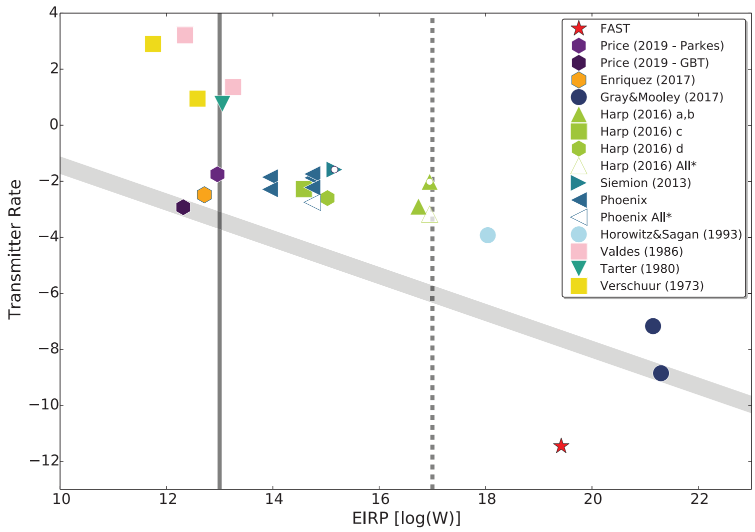

Fig. 8 Transmitter rate (or rarity of ETI transmitter) vs EIRP limit for a survey of the Andromeda Galaxy with FAST compared to all the previous significant SETI surveys. The *solid line* presents the EIRP of modern day narrow-band planetary radars and the *dotted line* is the speculative EIRP of a Kardashev Type I civilization. The *filled region* represents current limits placed by some of the sensitive modern-day surveys. The *red star* signifies the expected transmitter rate limit with a 6-hour observing campaign of the Andromeda Galaxy employing FAST's 19-beam receiver, which achieves much better sensitivity than the current limits (see Enriquez et al. (2017) and references therein for a more detailed discussion).

Recently, there have been ongoing efforts to classify various modulation types using CNNs and Deep Neural Networks (DNNs) for real-world applications (see O'shea et al. 2018 and Zha et al. 2019 for detailed discussions). Figure 5 displays one such example of ten artificially generated modulation signals across a wide range of frequencies from Zha et al. (2019). Moreover, in a US-based startup, *DeepSig*[9], members of the *Breakthrough Listen* team have utilized datasets provided by the US Army Rapid Capabilities office's Artificial Intelligence Signal

[9] `www.deepsig.io` has provided labeled real-world RF spectrum datasets[10] of around 24 modulation types for ML algorithm development. Such complex signals, although anthropogenic in nature, constitute a completely new class of signals which has never been comprehensively searched for in SETI applications.

Classification challenge. In the challenge, labeled datasets containing 24 modulation classes were provided with six degrees of SNR. The *Breakthrough Listen* team was successful in developing a CNN based classifier to achieve 95% prediction accuracy for the high SNR signals[11]. A t-SNE plot embedding these 24 modulation signals with well-separated clusters in 2-dimensional space is shown in Figure 6.

We plan to deploy a similar signal modulation analysis pipeline incorporating energy detection and modulation classification via a CNN classifier in collaboration with the *Breakthrough Listen* team. Such signal searches require recording of baseband raw voltages which would be possible to carry out with the proposed computing cluster in collaboration with the *Breakthrough Listen* team (see Fig. 1). One of the challenges of these searches is that a large fraction of the RFI tends to utilize one of a limited number of modulation schemes. However, sky localized modulation patterns of known and unknown types are of great interest to SETI. The FLAN provides a unique opportunity to scrutinize such signals using its coverage from 19 independent sky pointings with a small but significant overlap. Anthropogenic signals are likely to appear in multiple beams while a real sky localized signal – originating from a point source – can cover three to four nearby beams. A schematic of such a pipeline is displayed in Figure 7. Such multi-beam coincidence mappings have been successfully utilized in searches for the FRBs at other telescopes with multi-beam receivers (see for example Price et al. 2019). For FRBs, a comparison of detected time-stamp, dispersion measure and SNR can be carried out across all beams for every candidate. Similarly, for every detected modulation signal, corresponding time-stamp, modulation type, range of signal frequencies and SNR can be compared across all beams. We plan to employ such a technique to significantly reduce the number of false positives for such modulation signal searches with FAST.

Thus, such techniques could allow a sensitive search with FAST for modulated signals from ETIs towards the targets mentioned in Section 3. Furthermore, the *Breakthrough Listen* team has also developed CNN based ML classifiers to detect narrow-band (Zhang et al. 2018) and dispersed pulses (Zhang et al. 2018) which are also possible to deploy.

[11] `https://github.com/moradshefa/ml_signal_modulation_classification`

5 SENSITIVITY AND RARITY OF ETI TRANSMITTER

The required power for a certain ETI transmission to be detected depends on its directionality and other characteristics of the signals. We thus introduce the EIRP (Enriquez et al. 2017) as

$$\mathrm{EIRP} = \sigma \frac{4\pi d_\star^2}{A_{\mathrm{eff}}^R} \frac{2kT_{\mathrm{sys}}}{\sqrt{n_p t_{\mathrm{obs}} \delta\nu}}\ , \qquad (2)$$

where σ is the required SNR, $\delta\nu$ is the bandwidth of the transmitted signal, t_{obs} is the integration time for the observation, A_{eff}^R is the effective aperture of the receiver on Earth, n_p is the number of polarizations, and $d_\star$ is the distance between the transmitter and the receiver, i.e., distance to the star.

It is straightforward to estimate the required transmitting power to be detected for any source at a certain distance. Barclay et al. (2018) estimated that the median distance of stars with potential exoplanets that *TESS* will find to be around 200 light years. For a FAST-equivalent system of 300 meter aperture with a 70% antenna efficiency, the required EIRP is of the order of $1.9{\times}10^{11}$ W with a 1 Hz channel with 5-minutes of integration. Similarly, we also estimated EIRP limits at other wavebands in Table 1. It should be noted that humans routinely produce planetary radar signals with EIRP of the order of $\sim$$10^{13}$ W, which is higher than EIRP limits at all wavebands in Table 1. Thus, FAST will be able to put tighter constraints on any putative narrow-band signals towards stars with newly discovered exoplanets in the solar neighborhood.

For the survey of the Andromeda Galaxy, as depicted in Figure 3, we can easily cover the entire galaxy using just 21 hexagon patterns, which correspond to 84 pointings. With 10 minutes of integration time per pointing, FAST will be able to detect an EIRP of $2.4{\times}10^{19}$ W at the 0.77 Mpc distance of Andromeda.

This is three orders of magnitude higher than the total energy budget of a Kardashev Type I civilization ($\sim$$10^{17}$ W) but significantly lower than the energy budget of Kardashev Type II ($\sim$$10^{26}$ W) and Type III ($\sim$$10^{36}$ W) civilizations. Thus, such a dedicated survey will be able to put tight constraints on the presence of a transmitting Type II and Type III civilization among the 1 trillion stars in the Andromeda Galaxy.

5.1 Rarity of ETI Transmission Limit Compared with Other SETI Surveys

As mentioned in Section 1, over the past 60 years several SETI surveys have been carried out using a number of radio telescopes. These surveys include targeted searches towards nearby stars and nearby galaxies, and blind surveys of the sky. Enriquez et al. (2017) suggested a quantitative comparison parameter to compare these different SETI surveys. The rarity of ETI transmitters or transmitter rate is one possible way to compare these surveys. This parameter can be defined as,

$$\textit{Transmitter rate} = \log\Big(\frac{1}{N_{\rm stars}\nu_{\rm relative}}\Big). \quad (3)$$

Here, $N_{\rm stars}$ is the number of stars surveyed and $\nu_{\rm relative}$ is the relative bandwidth of radio spectrum covered. Figure 8 displays the transmitter rate as a function of sensitivity for these surveys. It can be seen that a 14-hour (84 pointings $\times$ 10-minutes) survey of the Andromeda Galaxy, utilizing FAST's 19-beam receiver, will be well below the most sensitive limits placed by all the earlier SETI experiments.

6 SUMMARY

FAST is the largest single-aperture radio telescope in the world and provides unprecedented sensitivity. In a collaboration with *Breakthrough Listen*, we have equipped the FLAN multi-beam receiver of FAST with a SETI pipeline, namely, *FAST-SetiBurst*, which has been tested targeting GJ 273 b, one of the closest known exoplanets and derived an EIRP detection limit of 7×10^{10} W. Based on these characteristics of the FAST SETI systems, we outline two unique FAST SETI experiments, both of which will push the current limits placed by earlier studies. First, a survey of the Andromeda Galaxy (M31) will detect an ETI with EIRP $> 2.4\times10^{19}$ W, corresponding to a comprehensive coverage of Kardashev type II and III civilizations in an external galaxy. Second, a survey of *TESS* exoplanets will detect an ETI with EIRP $> 1.9\times10^{11}$ W, which is well within the reach of current human technology. Along with narrow-band signal searches, we will also deploy comprehensive searches for artificially-dispersed pulses and modulated signals towards all targets. FAST will provide meaningful limits on possible ETI transmitters coincident with these targets and help answer humanity's oldest question: are we alone?

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