Direct Access to GEO Satellites: An Internet of Remote Things Technology

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Abstract—Satellites could guarantee ubiquitous service for devices in the Internet of Things (IoT) that are at remote locations without terrestrial services. The direct access of small and power-efficient terminals to satellite networks enables new services without the need of any terrestrial infrastructure. So far, the direct access to satellites in the geostationary earth orbit (GEO) has not been considered at higher frequency bands, where sufficient spectrum is available for massive machine type communication (mMTC). This paper analyzes the main hurdles of such a link and presents a novel waveform called Unipolar Coded Chirp-Spread Spectrum (UCSS) that enables ultra-narrow-band (uNB) communication with random multiple access between devices in the Internet of Remote Things (IoRT) and GEO satellites. We analyze UCSS by simulations and present a successful over-the-air transmission with a testbed operating at Ku-band. By that, it is verified that uNB mMTC via satellite is possible using the currently available resources in space.

I. INTRODUCTION

Machine type communication (MTC) or machine-to-machine (M2M) communication via satellite are currently a hot topic for satellite providers and funding agencies [1]. The direct access of narrow-band (NB) Internet of Things (IoT) devices to non-terrestrial networks in low earth orbit (LEO) and geostationary earth orbit (GEO) is a topic of the future research for 5G as recently stated by 3GPP in [2].

Terrestrial low-power wide-area network (LPWAN) solutions enable the transmission of small data packets from very small devices at minimum power consumption over distances of several kilometers. They are, therefore, attractive for a vast variety of applications in the IoT [3]. If such devices are used for the tracking of mobile objects or devices, a coverage of the employed IoT service over the area of interest is required. An additional satellite link for such devices would guarantee ubiquitous service, especially in remote locations and areas without terrestrial infrastructure [4].

Typical use-cases for the application of satellite communication (SATCOM) in the Internet of Remote Things (IoRT) either make use of a terrestrial IoT base-station with satellite back-haul or consider the direct access of devices to the satellites. It is intended to establish a direct access either to LEO satellites or to satellites in the GEO at L- or S-band [2]. Available solutions for NB SATCOM comprise a relatively large antenna and, due to the limited resources in the frequency band used, cannot handle massive numbers of subscribers. To enable massive machine type communication (mMTC) in the IoRT, higher frequency bands need to be made accessible for satellite based NB communication [1].

A system of LEO satellites could enable reduced terminal size and weight while increasing the number of users of global satellite communication [5], [6]. However, constant connectivity of users demands a very large number of satellites (>60) that route information among each other. Such a constellation of LEO satellites affords considerable financial and regulatory effort and is currently not available for mMTC. By contrast, three GEO satellites, with the exception of the polar regions, are already enabling global availability. So far, however, there are only systems that transmit data to GEO satellites with compact antennas at frequencies in the L-band or S-band [5], [7]–[9]. At higher frequency bands regulatory provisions for the protection of other systems and adjacent satellites severely limit the maximum allowable transmit effective isotropic radiated power (EIRP) and the long distance of more than 35.786 km makes data transmission at low transmit power nearly impossible. To the authors’ best knowledge, no system or waveform has been considered or standardized that is able or designed to close the challenging link between very small IoT devices and GEO satellites at C-band or above.

For MTC via satellite at L- or S-band, so-called supervisory control and data acquisition (SCADA) systems have been developed that apply scrambled coded multiple access (SCMA) or interleave division multiple access (IDMA) together with spreading to enable low-rate communication together with multiple access [10]. These so-called non-orthogonal multiple access (NOMA) class of schemes employ a low-rate forward error correction (FEC) and different scramblers or interleavers for user separation. A joint multi-user decoding with interference cancellation allows multiple users accessing the network non-orthogonally. For acquisition and synchronization, these waveforms either apply a unique word (UW) [8] or a chirp sequence [11] as preamble. Different UWs or chirps are used for the signals of different users to enable a separation within the sum signal at the receiver. However, the available spectrum at L- or S-band is very limited and the available services cannot handle a huge number of devices for mMTC.

In this work, we focus on the direct access of preferably small terminals to GEO satellites in frequencies of the C-band or above. We consider ultra low data rates with only a couple of bits per second and a burst transmission with random multiple access. This is sufficient for many applications, such as the transmission of sensor values, tracking, or emergency messages.

We present test results for a novel modulation format
called Unipolar Coded Chirp-Spread Spectrum (UCSS), first proposed in [12], that is designed to enable ultra-narrow-band (uN) transmissions in an effective manner with low hardware requirements at the transmitter and low effort for the acquisition and synchronization at the receiver.

In section II, the considered GEO SATCOM link is described and a link budget is calculated. Section III describes the challenges for a direct access to GEO satellites. The proposed waveform is summarized in section IV together with simulation results. In section V, we present the results of an over-the-air demonstration of the proposed waveform. We conclude the paper in section VI.

II. SYSTEM MODEL

In the following, we consider the channel between a large number of devices in the IoT transmitting via a transparent GEO satellite to a gateway station that serves as a common receiver as shown in Fig. 1. The signal $x_m(t)$ of the $m$-th user is transmitted at an EIRP of $\text{EIRP}_{\text{Tx},m}$. The receiving satellite antenna is characterized by the figure of merit $G_T$ in dB. The total path loss of the uplink channel is $G_{\text{UL},m}$. The signal power over the noise density $N_0$ in the uplink $\left(\frac{S}{N_0}\right)_{\text{UL},m}$ in dB is then given by

$$\left(\frac{S}{N_0}\right)_{\text{UL},m} = 10\log\left(\frac{\text{EIRP}_{\text{Tx},m} G_{\text{Rx},m}}{k}\right) + \left(\frac{G_T}{G_{\text{UL},m}}\right)_{\text{sat}}$$

where $k$ stands for the Boltzmann constant. If the contribution of the downlink to the overall signal to noise power ratio (SNR) is negligible, or if the satellite is regenerative, the overall SNR of the $m$-th user is $\left(\frac{S}{N_0}\right)_m \approx \left(\frac{S}{N_0}\right)_{\text{UL},m}$. The energy per bit over the noise density is approximately given by $E_b/N_0 \approx \left(\frac{S}{N_0}\right)_m - 10\log(R_b)$, where $R_b$ stands for the user bit rate.

To give an example for the achievable data rate, we provide the power budget for a link at Ku-band to a GEO satellites spot beam with $G_{\text{sat}} = 5\text{dB/K}$ at center of coverage. We assume an IoT device with $\text{EIRP}_{\text{Tx},m} = 23\text{dBm}$ transmitting at 14 GHz, and a path loss of $G_{\text{UL},m} = -207\text{dB}$. For the example considered, the signal power over the noise power density comes out to be $\left(\frac{S}{N_0}\right)_m = 19.6\text{dB/Hz}$ which gives a channel capacity of 60 bit/s in a bandwidth of 30 Hz. If we assume a binary phase-shift keying (BPSK) transmission with code rate 0.5 in 30 Hz, it would theoretically be possible to transmit a user bit-rate $R_b = 15$ bit/s at $E_b/N_0 = 7.8\text{dB}$. This means a device might transmit its position, which has been source coded to a size of 45 bits for instance, in a timespan of 3 s. The latency of the transmission to a GEO satellite has the same diameter. The satellite antenna at the satellite has the same diameter.

and back to earth is dependent upon the location on earth relative to the satellite. Typical values are between 240 ms and 270 ms. The low transmit power of only 23 dBm for the assumed device allows the design of very compact terminals not much bigger than a wrist watch.

III. ULTRA LOW RATE COMMUNICATION

A. Limitations

In practice, a sufficient spreading of the signal is required to widen the occupied bandwidth. This is because the carrier frequency offset (CFO) is not constant over the duration of a symbol at ultra low rate and would shift the signal outside the matched filter at the Rx. In consequence, the signal power density is reduced by spreading, shifting the received signal below the noise floor. The acquisition of such a signal at an unknown timing and an unknown CFO requires huge effort which is also known from global navigation satellite systems (GNSS) . In addition, if the IoT transmitter is only transmitting in short blocks for a low percentage of time, the acquisition has to be repeated for every transmitted block. This would require a very high computational effort at the gateway station which is receiving the signals of many devices.

B. Acquisition of Ultra-Low-Rate Signals

In many modern communication systems the signal acquisition is achieved by a preamble. The length of the preamble must be sufficient to enable its detection in noise. It is a design parameter which usually is kept as low as possible to minimize the overhead. With communication at ultra low rate, the length of the preamble adopts a considerable time span. To provide an example we consider the optimal detection of a signal in Gaussian noise by the Newman-Pearson-Test as derived in [13, Sec. 7.2]. From the calculations there, we can derive the required energy of a signal over the noise power density $\left(\frac{E}{N_0}\right)$ for given probabilities of detection $P_d$ and false alarm $P_f$. For example, $\left(\frac{E}{N_0}\right) > 15.05\text{dB}$ is required for $P_f = 10^{-6}$ and $P_d > 0.999$. Thus, the length of the preamble is at least 350 ms if a link budget with $\left(\frac{S}{N_0}\right) = 19.6\text{dB/Hz}$ is assumed as calculated in section II. The length of the preamble is even longer in practice to obtain an appropriate fading margin. Not only that this is a very long time, which is not available for
data transmission, it is furthermore most likely that the stability of the applied oscillators does not allow such a long coherent integration without losses.

C. Correlation Gain Limited by Phase Noise

For the analysis of the achievable correlation gain, we use a phase noise model taken from [14], where the noisy signal $r(n)$ is calculated from the noise-free signal $x(n)$ by

$$r(n) = x(n) \cdot e^{j\phi(n)}.$$  

(2)

According to [14], the phase noise $\phi(n)$ is a sum of three independent noise processes.

$$\phi(n) = \phi_1(n) + \phi_2(n) + \phi_3(n)$$  

(3)

Each of the three phase noise contributions is modeled with following variances

$$\sigma^2_{PN} = \sigma^2_{PN,1} = 100 \cdot \sigma^2_{PN,2} = 10 \cdot \sigma^2_{PN,3}$$  

(4)

The model was applied and Monte Carlo simulations were performed for different values of $\sigma^2_{PN}$. The results presented in Fig. 2 show the reduced correlation gain with increasing phase noise.

The curve in green marked by a star (−∗−) depicts the correlation gain using a BPSK modulated pseudo random number (PRN)-sequence with $L_s = 70,000$ symbols as preamble. A similar correlation gain is achieved using a single chirp with length $L_s = 70,000$ symbols, as depicted in red and marked by plus signs (−+−). It is derived from the figure that with increasing phase noise, the PRN-sequence loses 4 dB of correlation gain compared to the chirp.

We are able to obtain about 5 dB more correlation gain if we apply an incoherent correlation technique as indicated by the curve in blue (−−−).

Here, we performed a coherent correlation over chirp sequences with length $L_s = 1009$ and an incoherent correlation over $N_s = 67$ sequences. It is derived from the figure that with increasing phase noise, this method gains about 5 dB correlation gain over conventional chirp correlation.

D. Validation by Measurements

We performed tests with real hardware to evaluate the achieved correlation gain in the presence of phase noise. Here we used an Ettus USRP B205 as transmitter (Tx) and an Ettus B210 receiver (Rx) that have been connected back-to-back. The free running oscillators operated at a carrier frequency of 5.87 GHz. They have been measured with a phase noise of $−82.62$ dBc/Hz at 1 kHz and $−91.80$ dBc/Hz at 100 kHz. We transmitted chirp sequences and performed a coherent correlation at the receiver. The correlation gain for every chirp has been calculated from the correlation peak level. This has been repeated for different correlation lengths and the results are depicted in Fig. 3 in red color (−+−). The curve presents the mean values for the correlation gain, while the bars indicate the standard deviation at certain correlation lengths. Additionally, we calculated the coherent correlation for $N_s = 67$ consecutive chirp sequences individually and summed up their absolute values. The results are depicted in blue color (−−−) in Fig. 3. It is obvious the incoherent correlation technique provides higher correlation gain with less deviation. Thus, the correlation in two steps enables a much more reliable acquisition. For this reason, we created a waveform using this kind of correlation for signal acquisition.

IV. UNIPOLAR CODED CHIRP-SPREAD SPECTRUM (UCSS)

A. Transmitter

In the following we give a overview of the proposed UCSS modulation and synchronization format. Details are found in [12]. Fig. 4 presents a block diagrams of the Tx and Rx. Each transmitted data block is encoded with a FEC code before it is modulated by a differential phase-shift keying (DPSK) modulator.

Every modulated symbol is multiplied with a single Zadow-Chu [15], [16] or constant amplitude auto-correlation (CAZAC) chirp-sequence (CS) which is referred to as a...
chirp-spread spectrum (CSS) technique [17]. This spreading provides us with a correlation gain proportional to the length of the CS. Other applications of CSS are found in radar systems, military communications, ranging systems, and robust communication at low power spectral density. Signals spread by a chirp occupy a broad band of the spectrum and provide enhanced protection against interference, unwanted detection, multi-path propagation, frequency shifts from Doppler shifts, or oscillator inaccuracy [17]–[19]. CSS is often the choice for applications requiring high power efficiency and low data rates. In particular, IEEE 802.15.4a specifies CSS as a technique for use in Low-Rate Wireless Personal Area Networks (LR-WPAN) [20]. However, the terrestrial standards and waveforms are not designed to support cover rates that are sufficiently low to close the link considered here.

In the next step, before the signal is transmitted, we insert short pauses into the time signal between the chirps by inserting dummy samples. The upper diagram in Fig. 5 shows an example for the real-part of a base-band transmit signal. The pause times between the chirps are chosen according to an example for the real-part of a base-band transmit signal. The pause times between the chirps are chosen according to a unipolar code. Such codes are also called optical orthogonal codes (OOCs) and have been investigated for multiple access in optical fiber communications [21]. OOCs are unipolar sequences, for example, consisting of Zero-Bits and One-Bits, with good auto- and cross-correlation properties [22]. In the following we use the construction method in [23] for the OOC due to its low complexity. There it has also been proven that the auto-correlation of any codeword excluding the zero shift has strictly values of $\lambda_a \leq 2$. The cross-correlation of any two codewords is always $\lambda_k \leq 4$. Table I shows exemplary codewords for a code with $N_{ooc} = 4$ different words and the number of Ones $\beta = 5$ according to [23]. In the following we create codewords of sufficient length ($\beta = N_s$) to support the desired number $N_s$ of CS within a transmitted block.

We assign different codewords to different users and, by that, we create coded correlation signals that are distinguishable at the receiver by applying one correlation per codeword. Different users employing different codewords are supposed to transmit asynchronously at the same time in a random-access scheme. The number of Ones of two different OOC words that interfere within the cross correlation is limited by $\lambda_k$ during the design of the code. Thus, by distributing the codewords in the transmitted block according to these codes, we can ensure that the number of collisions at the receiver is limited, too. As a result, we created a method to identify the signals of different users at the gateway and at the same time separate users transmitting simultaneously.

### B. Receiver

At the receiver, where the transmitted signals of all users interfere, the received signal is first correlated with the CS, which can be considered as a CSS despreading. Hence, if all users share a single CS, at the gateway only one CSS despreader is required at the receiver to despread the signals of all transmitting users.

The correlation result contains a correlation peak for every transmitted symbol by any of the users. A collision at the Rx occurs when two or more symbols have been received at the same time. The unipolar coding at each Tx ensures that the number of collisions between two Tx stations is limited to a maximum number, which is a design parameter of the used OOC. The diagram in the middle of Fig. 5 shows the result of the first correlation of the received signal with the CS. To identify the users that have been transmitting, the result of the first correlator is non-coherently correlated a second time with a reference signal that contains the information about the unipolar codeword. This second correlation could be implemented with a low effort. It is performed for each of

![Flowgraph of the proposed modulation scheme (UCSS) with transmitter and receiver](image)

**Fig. 4.** Flowgraph of the proposed modulation scheme (UCSS) with transmitter and receiver

**Fig. 5.** Examples for the transmit signal and correlation results with $L_s = 100$ and $N_s = 17$
the potentially transmitting users, while the first correlation is only required once for each CS used. An example for the result of the second correlation is shown in the lower part of Fig. 5, where we can observe a single peak per transmitted user data block. A transmitted signal is detected if the correlation result of the second correlator exceeds a certain threshold. In the next step the timing is recovered and the DPSK symbols are localized within the output of the CSS despreader (the first correlator) and are differentially demodulated. After the decoding, we obtain the transmitted bit-sequence as the FEC corrects errors due to noise, interference and signal collisions.

### C. Simulation Results

The proposed waveform has been tested by simulation. The parameters for the transmit signal are provided in Table II. Simulations in additive white Gaussian noise (AWGN) assuming perfect synchronization, no channel fading and no phase noise have been carried out with different numbers $N_u$ of users transmitting simultaneously. The signals of the individual users have been shifted in time randomly to simulate unsynchronized random multiple access. The simulation results are presented in Fig. 6 showing the frame-error rate (FER) over the $E_b/N_0$. The figure reveals that with UCSS we are able to transmit with FER of $1 \times 10^{-3}$ at $E_b/N_0 = 8$ dB. If more users are transmitting simultaneously, interference is added to the channel. In our simulations, we do not incorporate the interference in $N_0$. With multiple users transmitting, a better $E_b/N_0$ is required for the individual user, as a small amount of interference between the users exists. Nevertheless the results show that the interference of other users is quite small and the waveform is suitable for random multiple access.

### V. OVER-THE-AIR DEMONSTRATION

The feasibility of ultra-low-rate communication with UCSS has been demonstrated by an over-the-air (OTA) demonstration. Therefore we implemented the waveform into a software defined radio (SDR) based testbed. We transmitted 64 bits within blocks using DBPSK modulated chirps of length $L_x = 1009$ and a rate 1/2 BCH code as FEC. The symbol rate after spreading has been set to 12.5 kHz, which corresponds to a user bit rate of 5.7 bit/s. As transmitter we used an Ettus B205 USRP SDR and a standard block up-converter (BUC) to shift the signal to the carrier frequency of 14.1 GHz. A rectangular patch with dimensions $10.7 \text{ mm} \times 9.3 \text{ mm}$ as depicted in Fig. 7 served as transmit antenna. The signal has been received by a transparent bent-pipe GEO satellite and relayed towards the ground station antenna of the Munich Center for Space Communications in Neubiberg, Germany. The signal has been received by a 7.6 m dish antenna, down-converted and sampled by an Ettus B210 SDR. After the receive signal processing, which includes detection, clock and frequency recovery, demodulation and decoding, we evaluated the transmitted information bits.

The test results contain all blocks transmitted during a total time of 4h with cloudy sky conditions. We varied the transmit EIRP between $-12 \text{ dBW}$ and $-7 \text{ dBW}$ to achieve statistics for the SNR values at the receiver. The results are presented in Table III, which shows the number of transmitted data blocks and the number of blocks that have been received without error. These results demonstrate very well

### TABLE II

**Simulation parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>chirp sequence (CS) length $L_x$</td>
<td>1009 symbols</td>
</tr>
<tr>
<td>nr. of chirps per frame $N_x$</td>
<td>134</td>
</tr>
<tr>
<td>modulation</td>
<td>2-DPSK</td>
</tr>
<tr>
<td>FEC coding</td>
<td>rate 1/2 BCH</td>
</tr>
<tr>
<td>user bits per frame $N_{bit}$</td>
<td>64</td>
</tr>
<tr>
<td>frame length $N_{frame}$ incl. dummy symb.</td>
<td>139,494 symbols</td>
</tr>
</tbody>
</table>

### TABLE III

**Test results**

<table>
<thead>
<tr>
<th>SNR in dB (measured)</th>
<th>Transmitted blocks</th>
<th>Nr. of error free blocks</th>
<th>Frame error rate (FER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-27</td>
<td>14</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>-26</td>
<td>32</td>
<td>3</td>
<td>0.9</td>
</tr>
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<td>0.67</td>
</tr>
<tr>
<td>-24</td>
<td>155</td>
<td>128</td>
<td>0.17</td>
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<tr>
<td>-23</td>
<td>257</td>
<td>241</td>
<td>0.06</td>
</tr>
<tr>
<td>-22</td>
<td>274</td>
<td>270</td>
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<tr>
<td>-21</td>
<td>61</td>
<td>61</td>
<td>0</td>
</tr>
</tbody>
</table>
the feasibility of uNB transmission to GEO satellites at higher frequencies. From the received data we calculated the FER which is presented in Fig. 8 together with simulation results for comparison. While we assume perfect synchronization and pure AWGN channel conditions in the simulation, the OTA test incorporates the errors from clock-, frequency- and SNR estimation. Furthermore, the transmission faces the real satellite channel that may incorporate time-dependent fading and of course severe phase noise from real oscillators. Thus, simulation results are shown including phase noise according to the model provided in section III-C. The resulting FER increases with higher values for the phase noise variance $\sigma_{PN}^2$. This indicates that the amount of phase noise present in the test system is limiting the system performance. However, we recall that the presented tests are intended a feasibility check of the waveform. No system optimization has been performed so far. This is left for future work.

VI. CONCLUSION

In this paper we investigated the narrow-band (NB) radio link between small devices in the Internet of Things (IoT) and satellites in the geostationary earth orbit (GEO) at higher frequency bands. We demonstrated that by the application of chirp-spread spectrum (CSS) and unipolar coding, a waveform is created that enables robust acquisition in the presence of phase noise. This novel ultra-narrow-band (uNB) waveform which we call Unipolar Coded Chirp-Spread Spectrum (UCSS) enables direct access to satellites in the GEO at center frequencies in the C-band or above. We performed simulations using UCSS and showed that it can handle multiple users transmitting simultaneously in a random multiple access scheme. Furthermore, we presented the results of a first over-the-air transmission at Ku-band and showed that we can successfully transmit towards a satellite in the GEO at a center frequency of 14.1 GHz. These results provide evidence for a possible application of massive machine type communication (mMTC) via satellite for devices at remote locations without terrestrial service.

Fig. 8. Frame error rate (FER) over the signal-to-noise ratio (SNR); results from over-the-air demonstration and simulation in comparison.

REFERENCES