An asynchronous high-throughput random access protocol for low power wide area networks

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***Abstract*—Among the design aspects that limit the network capacity of low power wide area networks (LPWAN), the adoption of an appropriate random access (RA) medium access control (MAC) protocol plays a fundamental role. Recently, ultra narrow band (UNB) networks, which operate over Time- and Frequency-Asynchronous ALOHA (TFAA), have emerged as a novel alternative to spread spectrum communications for LPWAN applications. While the UNB TFAA approach fulfills with the primary requirements of LPWANs, namely low power consumption, low terminal cost and long range communication capabilities, its throughput and packet error rate (PER) performance is rather poor. In this paper, we propose Contention Resolution Time- and Frequency-Asynchronous ALOHA (CR-TFAA), an enhancement of TFAA which is in line with recent advances on asynchronous RA schemes, such as Asynchronous Contention Resolution ALOHA (ACRDA). Numerical results show that the proposed technique provides a remarkable throughput-PER performance. Moreover, compared to ACRDA under similar conditions, CR-TFAA provides better PER performance over practical channel loads.**

***Index Terms*—LPWAN, Random-access, multiple access, ALOHA, IoT, M2M.**

I. Introduction

Low Power Wide Area Networks (LPWAN), also known as Low Throughput Networks, are currently taking increasing relevance in the development of the Internet of Things (IoT) and Machine-to-Machine (M2M) communications. According to recent forecasts, by 2020 LPWANs will represent 26% of the total IoT connectivity, with an expected compound annual growth rate of 90% over the period 2016-2020 [1], [2].

Unlike mobile networks, the design of LPWANs has been oriented to low data rates and low-consumption technologies, which allows for extremely low overall service costs (including both terminal and network access) and at the same time brings up new perspectives for the development of novel IoT applications. The lack of a leading industrial LPWAN standard, together with the inability of current mobile networks to provide cost-effective and low-consumption M2M services, has given space to the development of several proprietary solutions, among which we may mention LoRaWAN, Weightless, On-Ramp and Sigfox. According to the underlying physical (PHY) layer, the radio access techniques adopted by these systems can be generally classified into two main groups: spread-spectrum (SS) and narrow band/ultra narrow band (UNB) transmission (generally speaking, UNB differs from conventional narrow band systems because in the first the transmission bandwidth is comparable to the oscillator instability range. For a more detailed description of the UNB technique, the reader is referred to [3]). While SS techniques have been widely studied over the last decades, the UNB approach has only gained attention recently due to the rapid expansion of Sigfox networks, which are based on this radio access technique.

Regardless of the PHY layer design, the Media Access Control (MAC) layer of LPWANs typically relies on random access (RA) schemes. Indeed, RA is sometimes the more efficient MAC solution considering the low traffic duty cycles and the short packet sizes that characterize typical LPWAN applications. Further, the use of *asynchronous* RA schemes is appealing because it avoids the requirement for slot time synchronization, which has implications in terms of terminal cost and power consumption, and may also reduce the overall network capacity if the use of external reference signals (e.g. GPS) is impractical or unfeasible.

Asynchronous RA schemes have been introduced more than three decades ago with the well-known ALOHA protocol [4]. In ALOHA, packets are transmitted as soon as they are generated without following any type of coordination. Despite its simplicity, ALOHA provides a poor throughput performance, achieving a maximum of $T = 1/(2e) \simeq 0.18$ packets/slot under the collision channel model. Soon after the introduction of ALOHA, it was shown [5] that by simply accommodating packet transmissions into time slots it was possible to increase the ALOHA throughput, getting a maximum of $T = 1/e \simeq 0.36$ packets/slot. Thus, slotted ALOHA-based protocols have being widely employed in many common systems, including mobile (terrestrial) and satellite networks, where the use of a RA channel is always required (*e.g.* for connection set up or demand assignment).

With the recent advances on signal processing and the development of cross-layer RA design approaches, a new generation of slotted RA protocols capable of providing high throughputs at low packet error rates (PER) is emerging. In general, these protocols are characterized by the use of time diversity—which is achieved by transmitting two or more replicas of a packet over a frame structure spanning several time slots—, low-rate forward error correction (FEC) and successive interference cancellation (SIC) at the receiver side (see for instance [6–8]). Based on the same principles, high-throughput RA schemes of the asynchronous type have also been proposed recently. One of the first contributions in this area appeared with the introduction of Contention Resolution ALOHA (CRA) [9]. Based on the Contention Resolution Diversity Slotted ALOHA (CRDSA) [6] framework, CRA relaxes the synchronization requirements of CRDSA by allowing packet replicas being freely transmitted within the boundaries of a frame. Hence, synchronization is still required but at frame level instead of slot level. By contrast, in [10], Asynchronous Contention Resolution Diversity ALOHA (ACRDA) is presented as a fully asynchronous version of CRDSA, yielding even higher performances. Proposed as the access method for a satellite-based M2M network, the Enhanced-Spread Spectrum ALOHA (E-SSA) protocol [11] probably achieves the highest performance among the asynchronous RA schemes reported in the literature. However, as the name implies, it relies on spread spectrum techniques.

In this paper, we introduce a novel RA protocol that combines Time- and Frequency-Asynchronous ALOHA (TFAA) [12]—the access method employed in UNB LPWANs—with state-of-the-art signal processing techniques implemented in the modern high-throughput protocols cited above. The proposed protocol, named Contention Resolution Time- and Frequency Asynchronous ALOHA (CR-TFAA), also achieves a remarkable performance and looms as an interesting alternative to SS techniques to provide high-throughput RA in power constrained scenarios such as LPWAN and M2M communications.

II. Overview of TFAA

The TFAA access approach appears naturally in UNB LPWANs. Since the bandwidth occupied by a single transmission is comparable to the oscillator frequency uncertainty, it remains difficult to respect tight channel boundaries. Hence, the use of a Frequency Division Multiple Access (FDMA) approach is inefficient, as guard bands become significantly larger with respect to the signal bandwidth. Similarly, the use of a slotted time reference is not practical because of the heterogeneous propagation delays experimented by different terminal nodes, which entail additional synchronization complexity. As a consequence, in UNB TFAA packets are transmitted without coordination in both frequency and time domains.

Although having been only considered within the UNB context, there is in principle no reason why TFAA cannot be extended to other application scenarios. Some of the general advantages of TFAA include:

1) Frequency synchronization requirements are significantly relaxed. Packets can be transmitted over any random frequency within the system bandwidth. Frequency synchronization is handled at the receiver side. Thus, by avoiding the requirement for accurate oscillators, cheaper radio transmitters may be considered.
2) Robustness to Doppler shifts. Since the system is already designed to support a high amount of frequency uncertainty, relatively high Doppler shifts should be managed transparently. However, high Doppler effects may entail additional issues in UNB operation, as we discuss below.
3) Increased FEC collision resolution capabilities. The Multiple Access Interference (MAI) in TFAA can more easily be coped with the help of low-rate FEC. While this aspect was already identified in time-asynchronous schemes [9], it is also apparent when frequency-asynchronism is introduced [12].
4) Resilience to power imbalance. Unlike SS systems—whose throughput drops quickly in the presence of power unbalance [11], the throughput performance of TFAA increases in such conditions. This is an important feature in heterogeneous environments, such as LPWANs, specially in the absence of tight power control mechanisms.

In addition, a UNB TFAA radio interface allows to either increase the communication range or to reduce the required transmission power significantly, by reducing the transmission bandwidth below the levels required in conventional FDMA systems. This is one of the main reasons why UNB TFAA is interesting for LPWAN applications. However, TFAA introduces additional issues that must be taken into account. In particular, since there is an extra degree of uncertainty in the demodulation process, the receiver complexity is increased with respect to a typical ALOHA-like system. UNB TFAA has also gained attention within the context of satellite M2M systems. In [13], its application on low Earth orbit satellite systems is studied considering a collision channel model. In this scenario, it is shown that when the transmission rate is low compared to the Doppler rate, timing issues may also impact the MAC performance.

A. Throughput Performance of TFAA

Under the collision channel definition given in [12], a TFAA packet is assumed to be successfully transmitted over a time-frequency point (t_i, f_i) if and only if no other packet is transmitted over the region $[f_i - B, f_i + B] \times [t_i - T_p, t_i + T_p]$ (see Figure 1), where T_p and B are the packet duration and bandwidth, respectively. With this definition, and considering a total available system bandwidth W, $W > B$, it can be easily shown [12] that the TFAA throughput T for a given channel load G approaches

$$T = G \cdot \exp\left[-4G\right] \tag{1}$$

as $B/W \to 0$. Equation (1) is sketched in Figure 2, where the throughput of ALOHA is also included for comparison. While ALOHA clearly outperforms TFAA under the collision

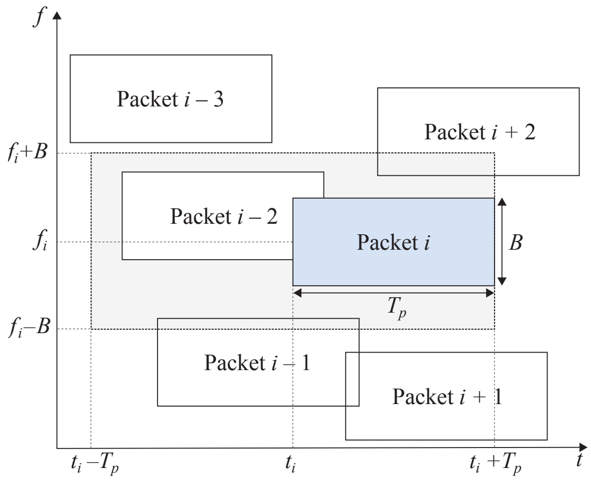

Figure 1. A two-dimensional representation of TFAA. The gray-shaded area corresponds to the set of points (t, f) over which any transmitted packet will interfere with packet i. For the collision channel model, the overlap of packets i and $i-2$ results in both packets being lost.

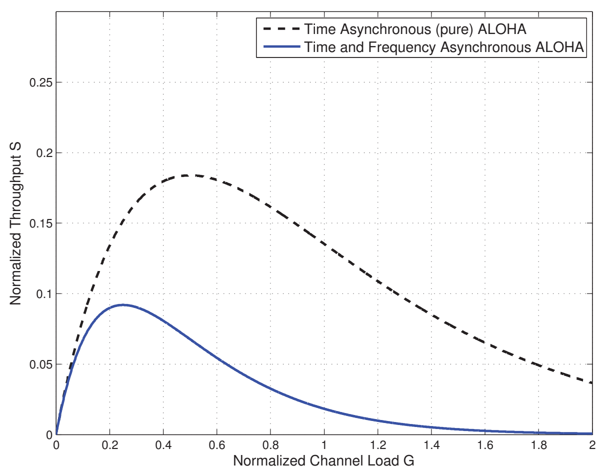

Figure 2. Normalized throughput versus MAC load for TFAA and pure ALOHA under the collision channel model.

channel model, this gap is significantly reduced when the packet error probabilities are computed taking into account the actual signal waveform [12].

B. Scalability Issues of UNB/TFAA Systems

From the results evoked above it is clear that the use of TFAA in its simplest form does not provide an efficient RA operation. In addition, a major drawback of LPWANs is that frequency reutilization is difficult due to the important area covered by a single access point. Exploiting collision resolution techniques at the receiver side is therefore an interesting alternative to improve the traffic capacity in UNB/TFAA LPWANs.

III. CR-TFAA System Model

In this section we provide a high-level description of the proposed CR-TFAA protocol. In order to facilitate the comparison with other relevant high-throughput RA schemes, the design approach we present here follows the main guidelines given in [6], [10]. In particular, the underlying PHY layer is based on turbo FEC and M-PSK modulation. Also, a sliding-window SIC receiver architecture is considered.

We consider an infinite population RA system with one central receiving node. The overall packet arrival process is Poisson with rate λ packets/s. The total available system bandwidth is W. By contrast, a packet transmission is contained within a bandwidth B and has a fixed duration T_p, as shown in Figure 1 (in general, B should be much smaller than W for a UNB signal). Each packet carries a payload of L_b information bits. The aggregate number of packet arrivals during T_p, that is, the offered traffic over the full band W, is noted $G_a = \lambda T_p$. Note that G_a is typically greater than 1 since in TFAA several packets can be transmitted and decoded simultaneously. Therefore, the *normalized* throughput is defined as

$$T(G) \triangleq G \times (1 - P_e), \tag{2}$$

where $G = G_a \times B/W$ is the *normalized* average channel load and P_e the PER. Thus, G represents the average offered traffic over a band B.

Packet transmissions are organized in virtual frames (VF), following the framework introduced in [10] for ACRDA. A VF has a duration $T_F = N_{\text{slots}} \times T_p$, where N_{slots} is the number of time slots per frame. When a new packet is generated at the MAC unit, a new VF is built and N_{rep} replicas of the packet are generated and placed in random locations within the VF, *i.e.* at random time slots and at random carrier frequencies, but taking care of selecting non-overlapping positions among the packet replicas. Assuming that the replicas' energy is fully contained within a bandwidth B, and that the system spectrum is centered at $f = 0$, the carrier frequencies must be selected within the interval $[f_m, f_M]$, where $f_m = -B([W/B] - 1)/2$ and $f_M = B([W/B] - 1)/2$.

In CR-TFAA we define the frame size $N_{t\times f}$ as the number of time-frequency points over which replicas can be placed without overlapping. It follows that $N_{t\times f} = N_{\text{slots}} \times \lfloor W/B \rfloor$. VFs are generated and transmitted asynchronously by each user terminal and thus arrive at the receiver with random time offsets. The main difference between the VF structure in ACRDA and CR-TFAA is that in the latter the VF spans a bandwidth much greater than the packet bandwidth, so that replicas can be freely transmitted within W. Figure 3 shows an example where the VFs from four different users are transmitted using $N_{\text{rep}} = 2$, $W/B = 10$ and $N_{\text{slots}} = 5$. Along with the L_b payload bits, each replica also contains a few extra bits where the relative position of the other $N_{\text{rep}} - 1$ replicas is indicated. Note that in the diversity scheme adopted here the VF time axis is divided in a discrete number of slots, while the frequency axis is not slotted. The reason for this is that defining frequency slots demands a certain amount of frequency synchronization and oscillator stability, which

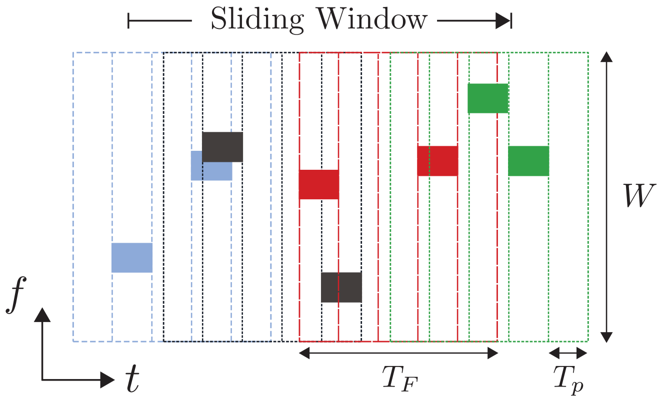

Figure 3. Frame structure in CR-TFAA. Virtual frames from four different users are represented with different colors.

cannot be achieved with UNB signals as discussed earlier [1]. The replicas' bits are FEC encoded, modulated using M-PSK and filtered using a square root rise cosine (SRRC) filter $g(t)$ with roll-off factor β. Thus, the signal associated with some replica k is modeled as

$$r(t) = a_k \sum_{l=0}^{L_p-1} d_k(l) g(t - lT) e^{j(2\pi f_k t + \phi_k)}, \tag{3}$$

where L_p is the packet length in symbols, a_k^2 the channel gain, the sequence $\{d_k(l),\ 0 \leq l < L_p\}$ represents the replica's symbols, T is the symbol duration, $f_k \sim \mathcal{U}[f_m, f_M]$ is the carrier frequency and $\phi_k \sim \mathcal{U}[0, 2\pi]$ a random phase offset. It is assumed that the replicas are affected by a log-normal flat fading process of mean μ and standard deviation σ dB, and additive white Gaussian noise (AWGN). Doppler effects are not taken into account (all nodes are assumed to be in fixed positions).

At the receiver side, the incoming signal is sampled using a sliding window approach as in [10]. The sliding window spans W_{VF} [2] VFs with a step size ΔW_{VF}, expressed as a fraction of one VF. The SIC process starts by scanning the sliding window samples over the whole system bandwidth in order to detect the presence of replicas. When a replica is correctly located, it is demodulated through a matched filter detector and then turbo decoded. If the replica is successfully decoded, its interference contribution is removed from the sliding window buffer. The interference from other replicas of the same packet present in the sliding window is removed next. If not all of the packet replicas are fully contained in the sliding window, the packet information is stored until the remaining incoming replicas are received and removed. The SIC process is repeated a number of times up to a maximum of N_{it} iterations. Then, the sliding window is shifted in time by $\Delta W_{\text{VF}} T_F$ seconds and the process is repeated. Finally, since our goal in this paper is to study the performances that can be achieved by CR-TFAA, we consider an ideal SIC receiver that is able to locate the replicas and estimate the signal parameters perfectly [3].

[1] In practice, the use of frequency slots—even if oversized—is convenient as it allows to minimize the signaling overhead. In either case, the relative frequency position of a replica can only be given approximately in UNB.

[2] In [10] the sliding window length is denoted W. Here we add the subindex VF to avoid ambiguity with the system bandwidth W

IV. Numerical Results

A. Simulation Approach

A computer simulator closely following the model described in the previous section has been developed in order to test the performance of the CR-TFAA protocol. The packets of fixed length $L_b = 100$ bits are encoded through a turbo encoder of rate $\rho \simeq 1/3$ and modulated using M-PSK. The turbo encoder architecture follows the 3GPP standard also employed in [10]. For the SRCC filter roll-off factor, we have considered $\beta = 0.2$. The number of samples per symbol at the output of the SRRC filter is LW/B, where $L = 8$. We assume that packet arrivals can occur at any instant within the symbol duration T with a granularity of LW/B samples per symbol. In order to limit the simulation time, we consider relatively small values for the W/B ratio (*i.e.* $W/B = 5, 10$). It is noteworthy that these values are not representative of practical UNB LPWANs, for which the ratio W/B is in the order of 100 or greater. Thus, the results presented here are somewhat pessimistic since the use of higher values of W/B provides slight performance improvements. For the SIC receiver configuration we considered a sliding window length and step size $W_{\text{VF}} = 3$ VF and $\Delta W_{\text{VF}} = 0.15$ VF, respectively, and a maximum number of SIC iterations $N_{\text{it}} = 15$. In the absence of fading effects, the signal-to-noise ratio per symbol is set to $E_s/N_0 = 10$ dB. For the log-normal process affecting the channel gains a_k^2's, we consider two general cases: $(\mu, \sigma) = (0, 0)$ dB, for perfect power control and $(\mu, \sigma) = (0, 3)$ dB for power imbalance conditions. The simulation results are expressed in b/s/Hz taking into account an underlying spectral efficiency given by $\eta = \rho \log_2(M)$[4].

B. Semi-analytical Approach

It is also possible to approximate the CR-TFAA performance by extending the semi-analytical framework developed for ACRDA in [10]. The procedure can be resumed as follows. First, one has to take into account that the intensity of packet arrivals that collide with a given test packet is approximately doubled in CR-TFAA. Also, when computing the loop probabilities, the parameter N_{slots} should be replaced by the CR-TFAA frame size $N_{t\times f}$. Finally, we observe that the method employed in [10] to compute the error probabilities for a given number of colliding packets—which assumes a Gaussian distribution of the interference plus noise power—does not hold in CR-TFAA, specially when short packets are considered. Hence, the error probabilities for a given modulation and coding schemes have been obtained through computer simulations.

[3] Note that the ideal channel estimation hypothesis is commonly adopted in the related literature (see for instance [6], [9], [10]).

[4] The pulse shaping filter roll-off factor is not included for fair comparison with related works.

C. CR-TFAA without diversity

When the repetition degree is set to $N_{\text{rep}} = 1$, the VF notion is no longer required (*i.e.* $N_{\text{slots}} = 1$) and, from the transmitter point of view, the protocol operates as pure ALOHA. This configuration is interesting because 1) it can be readily implemented in existing UNB systems since most of the additional signal processing is performed a the receiver side and 2) it provides advantages in terms of demodulator complexity as the need for replica channel estimation and interference cancellation is avoided. In addition, since in this case $T_F = T_p$, the sliding window only spans W_{VF} times the packet length, which is also beneficial in terms of demodulator complexity. In the simulations we considered BPSK modulation and $W/B = 10$. The rest of the parameters are those detailed in Section IV-A. The performance results obtained under this scenario are shown in Figure 4. We observe that a PER below 10^{-2} can be guaranteed for channel loads up to $G \simeq 0.8$ b/s/Hz under power imbalance conditions and $G \simeq 0.6$ b/s/Hz for perfect power control. For a maximum PER of 10^{-3}, the achievable load is around $G \simeq 0.4$ b/s/Hz in both cases. This suggests that the performances reported for TFAA in [12] can be significantly improved by the use of simple SIC techniques and without requiring the transmission of additional packet replicas, which is explained by the fact that frequency randomization provides already a certain amount of diversity.

D. CR-TFAA with time-frequency diversity

Our interest in this section is to evaluate the performance of CR-TFAA exploiting time-frequency diversity and to contrast these results with those obtained with ACRDA. We observe that if the W/B ratio is set to 1, then $f_m = f_M = 0$. In this case, all replicas are transmitted over the same frequency $f = 0$ and the protocol operates exactly as ACRDA (thus, CR-TFAA can be considered as a generalization of ACRDA). Simulation results for CR-TFAA were obtained using $W/B = 5$ and $N_{\text{slots}} = 20$, while for ACRDA $W/B = 1$ and $N_{\text{slots}} = 100$. In both cases, $N_{\text{rep}} = 2$ and QPSK modulation is adopted. Note that, in order to provide a fair comparison, the same frame size has been considered for the two schemes ($N_{t\times f} = N_{\text{slots}} \times W/B = 100$). The results are presented in Figure 5, where it can be observed that both protocols provide very similar performances. In particular, the critical points (*i.e.* the values of G over which the system performance drops quickly) are very close. In terms of maximum achievable throughput, CR-TFAA is slightly below ACRDA under power imbalance conditions and is practically identical under perfect power control. It is worth noting, however, that CR-TFAA provides a PER performance that is at least about one order of magnitude below that of ACRDA for channel loads below $G \simeq 0.8$ b/s/Hz and $G \simeq 1.4$ b/s/Hz for $\sigma = 0$ and $\sigma = 3$ dB, respectively. In other words, the PER performance of CR-TFAA is superior over practical channel loads (*i.e.* below the critical points).

To further validate these results, in Figure 6 the performances obtained through simulations are compared with those given by the semi-analytical method for the perfect power control regime. As for ACRDA, we observe that the semi-analytical approach provides a lower bound for the PER—which is probably due to the simplifications in the loop probability analysis—but provides a good description of the protocol behavior. Also, it confirms that the CR-TFAA PER is improved with respect to ACRDA.

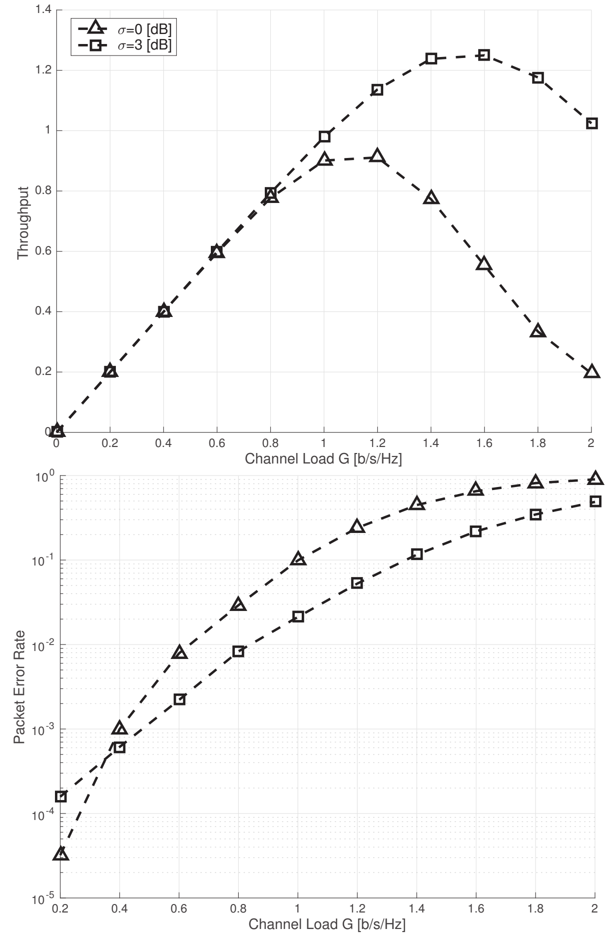

Figure 4. Throughput and PER performance of CR-TFAA without time-frequency diversity ($W/B = 10$, $N_{\text{rep}} = 1$, $N_{\text{slots}} = 1$, BPSK modulation, $E_s/N_0 = 10$ dB and turbo FEC $\rho = 1/3$).

V. Conclusion

In this paper, we have proposed and evaluated the use of SIC techniques in combination with TFAA, a pure ALOHA access approach where the packet transmissions are random in both frequency and time domains. The novel protocol, named CR-TFAA, can be regarded as a generalization of ACRDA and aims to improve the performance of LPWANs based on UNB. Numerical results for two main scenarios have been presented, namely with and without time-frequency diversity. In both cases, it is shown that CR-TFAA significantly improves the performance of TFAA. For the scenario including time-frequency diversity, the CR-TFAA performances were also compared with those of ACRDA.

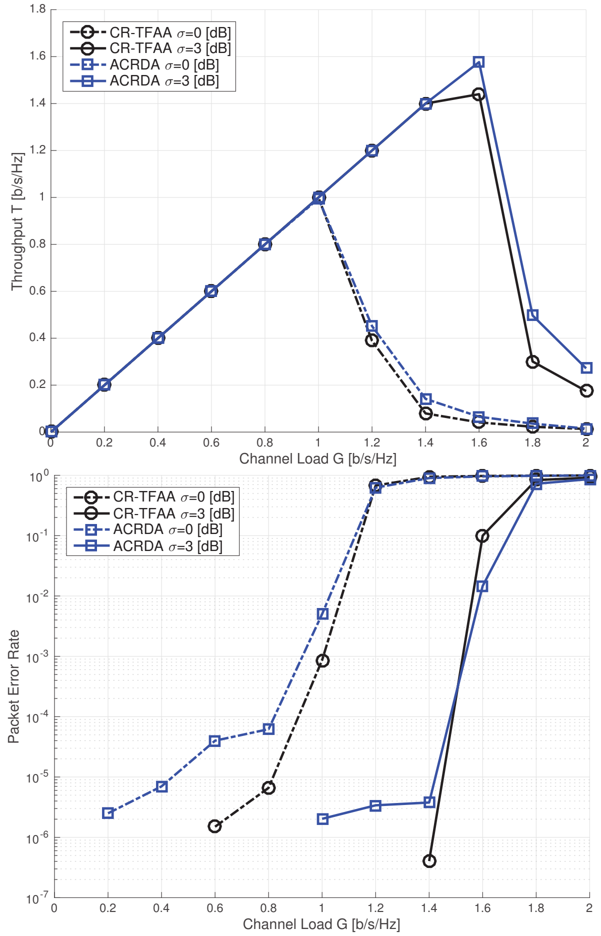

Figure 5. Throughput and PER performance of CR-TFAA with time-frequency diversity ($W/B = 5$, $N_{\text{rep}} = 2$, $N_{\text{slots}} = 20$, QPSK modulation, $E_s/N_0 = 10$ dB and turbo FEC $\rho = 1/3$) and ACRDA (only two parameters are changed in this case, namely $W/B = 1$ and $N_{\text{slots}} = 100$).

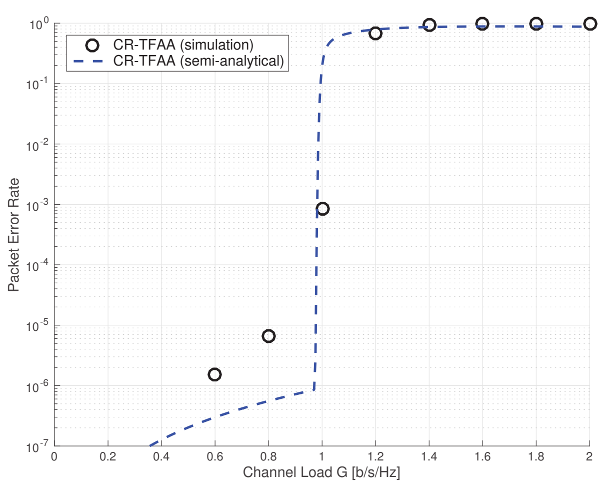

Figure 6. Simulation vs semi-analytical performance of CR-TFAA with time-frequency diversity ($W/B = 5$, $N_{\text{rep}} = 2$, $N_{\text{slots}} = 20$, QPSK modulation, $E_s/N_0 = 10$ dB and turbo FEC $\rho = 1/3$).

ACKNOWLEDGMENT

This study has been achieved thanks to the financial support of the VAN ALLEN foundation.

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