Unmanned Aerial Vehicles-Aided Internet of Things

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Contributor: Zihao Pan, Chen Xie, Heng Wang, Yimin Wei, Daoxing Guo

With the surge of Internet of Things (IoT) applications using unmanned aerial vehicles (UAVs), there is a huge demand for an excellent complexity/power efficiency trade-off and channel fading resistance at the physical layer.

Keywords: blind equalization ; continuous-phase modulation ; EM algorithm

1. Introduction

Driven by the explosive surge of Internet of Things (IoT) services for sixth-generation (6G) mobile communications systems, different new 6G use cases have been proposed and are under intensive research discussion recently, such as IoT industry automation, maritime machine-type communication networks, and other applications [1][2]. As one of the key technologies to achieve the vision of the Internet of Everything, UAVs have been widely used to perform diversified tasks [3][4][5] due to their low cost and flexible deployment.

There has been a recent surge of studies on the use of UAVs for IoT communication [6][7][8], such as data collection [9][10] and mobile edge computing [11]. However, with the dramatic increase in the number of connected machines, the number of IoT devices deployed worldwide is expected to grow to 75.4 billion by 2025 [12]. There is a growing demand for low complexity and high power efficiency in UAV-aided IoT communication due to the limited payload of the devices.

Continuous phase modulation (CPM) is suitable for power- and bandwidth-limited systems because of its good spectral efficiency and its higher power efficiency relative to linear modulations with comparable spectral efficiency. Moreover, the constant envelope property of CPM allows the nonlinear power amplifier (PA) to be operated at a high efficiency, which further increases the power efficiency of the system [13]. For battery-powered IoT nodes and UAVs, energy efficiency and cost are key factors because these devices are difficult to recharge or recycle once depleted. Therefore, CPM is one of the preferred modulation schemes in UAV-aided IoT communications systems due to its favorable low power consumption, which can greatly increase the life of terminal devices.

However, CPM transmission over multipath fading channels is a challenging task due to the high computational complexity in the receiver. If the design of the waveform is poor, it will reduce the overall power of the communications systems, even offsetting the increased power efficiency achieved by the PA. Therefore, researchers focus their attention on the receiver design at the physical layer for CPM over frequency-selective channels employing low data rates and short bursty transmissions, which is a fundamental tool to implement UAV-aided IoT. In general, the main contributions include the following:

- Researchers combed the literature related to CPM and summarized it in the **Table 1**.
- To meet the demands of low data rates and short-burst transmission scenarios of the UAV-aided IoT system, a short burst structure of CPM is designed, and a link-level simulation platform of the communications system is established on this basis.
- A low complexity approach for soft-input soft-output (SISO) blind equalization is proposed to achieve a fast and accurate blind equalizer in the UAV-aided IoT system. The first step utilizes the soft-output Lazy Viterbi algorithm instead of the Viterbi algorithm to perform the expectation step and obtain a low complexity expectation–maximization Lazy Viterbi algorithm (EMLVA), while the second step applies the BCA method to establish a set of initializers, denoted as the BCA initializers, which achieves a high global convergence probability.
- The blind turbo equalization for short-burst CPM is proposed based on the new SISO blind equalization with iterative detection, where the blind equalizer and decoder exchange extrinsic information in the form of log-likelihood ratios

(LLRs). To further improve the convergence of iteration and reduce the average iteration number, the decision-aided (HDA) algorithm based on weighted extrinsic information exchange is proposed.

- The blind turbo equalization based on EMLVA is proposed and evaluated on a link-level simulation platform. Simulation results show that EMLVA can obtain a good trade-off between complexity and BER performance. When the HDA with weighted extrinsic information is applied, the convergence of iterative detection and real-time performance can be further improved.

Table 1. Summary of the related work.

Classification	Ref.	Contribution/Methodology
Data-aided	[14]	**A generalized pilot symbol-aided demodulation method is proposed in a flat fading channel. The optimal filters for channel estimation are also presented.**
	[15]	**The estimate of the channel is realized by local B-splines.**
Statistics	[16]	**The second-order statistics of the signal for channel estimation is extracted for CPM by TXK.**
	[17]	**A fourth-order cross-cumulant matrix is extracted by the eigenvector method.**
MCMC	[18]	**A nonlinear signal model for GMSK and information symbols with implicit channel estimation by MCMC are developed.**
Adaptive equalization	[19]	**A forward adaptive SISO that considers the channel correlation in only one direction is proposed for MSK.**
	[20]	**A variety of the reduced state FA SISO is proposed.**
	[21]	**The thresholds of the RS-A-SISO algorithms are obtained by the density evolution technique.**
	[22]	**Derivation of the forward/backward adaptive algorithm.**
	[23]	**Derivation of the generalized forward/backward adaptive algorithm.**
HMM	[24]	**The BBW algorithm, as well as two variants, are proposed for CPM.**
	[25]	**A stochastic ML blind channel estimation is developed, and an approximate Cramér–Rao bound for CPM is derived.**
	[26]	**The Viterbi algorithm is applied within the EM algorithm.**
FDE	[27]	**The single-carrier frequency-domain equalization is used in the CPM signal for the first time.**
	[28]	**Laurent decomposition is used to realize traditional equalization (linear and decision feedback) and turbo equalization in the frequency domain.**
	[29]	**More iterative gain without matrix inversion.**

2. Unmanned Aerial Vehicles-Aided Internet of Things

In practical communications, the signals are transmitted over the fading channel and the channel response is unknown. In [14], a generalized pilot symbol-aided demodulation method based on the idea of inserting data-dependent symbols periodically was proposed for CPM in a flat Rayleigh fading channel. An optimal front-end filter was developed based on the mean-squared error (MSE) in the channel estimation process. Then, the channel estimates generated by the interpolation filter, together with the received signal, are input into a coherent CPM demodulator using the Viterbi algorithm. In frequency-flat fast-fading channels, Ref. [15] provided a data-aided channel estimation algorithm with local B-splines, and the results showed that there exists a minimum sampling interval proportional to the normalized fading rate for pilot insertion. However, when short bursts are considered, the data-aided channel estimation method can significantly increase the overhead-to-payload ratio. Similarly, low-complexity frequency-domain equalization for CPM [27][28][29] requires the addition of a cyclic prefix or unique words, which can also increase the overhead-to-payload ratio for short bursts.

As an alternative, blind channel equalization can recover the signal directly, without a training sequence. The author in [16] applied the Tong–Xu–Kailath algorithm to CPM by extracting the second-order statistics of the signal for channel estimation. The eigenvector method was used to identify the channel from a fourth-order cross-cumulant matrix under the GSM channel in [17], combined with turbo estimation. However, when applied to a low number of symbols, the statistical moments did not provide accurate channel estimation. In [18][30], the author developed a nonlinear signal model for GMSK rather than the conventional finite impulse response model. The information symbols were obtained by Bayesian inference based on Markov chain Monte Carlo (MCMC) with implicit channel estimation.

CPM and the multipath channel can construct a joint trellis, which can be represented by a finite state machine (FSM). Therefore, a forward adaptive SISO (FA-SISO) [19], which considers the channel correlation in only one direction, was proposed for MSK, which replaces the unknown channel by the least-mean-squared error for each hypothesis branch symbol. Then, due to the high complexity of FA-SISO, the author in [20] proposed various reduced-state A-SISO (RS-A-SISO) algorithms for complexity reduction at the same time. The thresholds of the RS-A-SISO algorithms were obtained by the density evolution technique in [21]. Another structure is the forward/backward adaptive algorithm. An exact expression for the soft metrics was derived when the unknown parameter was modeled as a Gauss–Markov process in [22], which can be estimated iteratively by the Kalman filter. The author in [23] employed the concept of bidirectional estimation in [22] and derived a generalized a posteriori probability of soft branch metrics.

The FSM can also be described by a hidden Markov model (HMM), and the Baum–Welch (BW)/EM algorithm allows for great likelihood estimation of the unknown parameters in the HMM. The batch-BW (BBW) algorithm, as well as two variants were proposed by Carles [24] for time-invariant channels. One is to split the received signal into several sub-blocks, producing different channel estimates in each, called the segmented batch-BW (SBBW) algorithm. However, the variant needs to avoid over-fragmentation because of a poor estimate from fewer data. An alternative algorithm called time-dependent BW (TDBW) was derived by introducing some linear constraints emerging from a linear FIR hypothesis on the channel. The author in [25] proposed an improved Baum–Welch algorithm to directly estimate the channel parameters, avoiding over-parameterization in the estimation problem. In [26], an algorithm for joint channel estimation and equalization by applying the Viterbi algorithm within an EM iteration was introduced, which was used to implement the E-step. However, the major drawbacks among the works cited above are relatively poor convergence with an inappropriate initializer and high complexity.

CPM serves as one of the preferred modulation schemes for the transmission of low data rates in the IoT uplink, suffering from the high complexity and poor convergence of the channel estimation at the receiver. Therefore, researchers propose a low-complexity blind equalization algorithm for short-burst CPM signals based on the HMM. The proposed blind equalizer significantly outperforms the traditional one in complexity, while keeping a similar BER performance, which helps the device achieve online real-time detection. In general, as the spectrum resources are limited and the number of connected devices is increasing day by day, CPM is a promising modulation scheme, which is suitable for battery-powered devices and is expected to play an important role in the physical layer design of UAV-aided IoT communications.

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