出國報告（出國類別：參加研討會）

改良型 Link-16/JTIDS 接收機於惡意脈波干擾環境下之效能分析

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摘　　要

Link-16戰術資料鏈路通訊系統為北大西洋公約組織成員國、美國及其盟國（包括台灣）現役之軍事通訊系統，其主要任務為支援三軍 聯合作戰中的「指揮」與「管制」作為。Link-16可提供艦艇、飛機與陸岸設施（如雷達站）間戰術資料的交換，以利戰場指揮官掌握全般戰場圖像，進而有效發揮聯合作戰之戰力。Link-16的通信終端裝置為「聯合戰術資料分配系統」(JTIDS），其特色包括Reed Solomon (RS)通道編碼、CCSK循環碼鍵移符號調變、MSK最小化鍵移波形調變等技術。為了以最經濟的方式來提升Link-16對抗惡意脈波干擾的能力，本研究係採用錯誤與抹除碼解碼(EED)以及雜訊正規劃結合的MSK(NNC/MSK)解調技術來取代原有之RS錯誤碼解碼與MSK解調技術。

錯誤與抹除碼解碼(EED)以及雜訊正規劃結合(NNC)並非最新的通訊技術，但是把這兩種技術合併運用於Link-16接收機，卻是全新的嘗試。為了讓效能分析順利地進行，本研究的假定包括理想的解跳頻與理想的訊息同步。再者，為了凸顯改良型Link-16/JTIDS接收機的效能，本研究的結果會與原系統的效能做客觀公平的比較。根據比較的結果發現，本研究所提出的改良型Link-16/JTIDS接收機在效能上優於原接收機；而當信號雜訊比較強且惡意干擾以較短的脈波攻擊Link-16時，改良型Link-16/JTIDS接收機能讓惡意的脈波干擾失效。換句話說，惡意的攻擊者只能退而其次使用較溫和的干擾方式，如全頻干擾(Barrage Jamming)。對於戰術資料鏈路系統的運用，國軍仍在啟蒙的階段；由於在戰時，戰術資料鏈路系統必定會遭遇敵人的電子攻擊，有關提升Link-16系統以對抗惡意干擾的相關研究，國內相關研發單位必須多加重視。

圖一、　Link-16 戰術資料鏈路系統運作示意圖。

本　　文

壹. 出國目的

此次公務出國的主要目的係發表個人所主持的100年度國科會研究計畫「非同調偵測之Link-16/JTIDS信號運用雜訊正規化結合技術對抗惡意窄頻干擾之研究」之先期研究成果。此研究計畫的論文（如附錄）於本年9月獲得IEEE（國際電子暨電機工程師協會）所主導的2011年「軍事通訊研討會」（Military Communication Conference 2011，簡稱MILCOM 11）的接受並獲邀至大會中發表。MILCOM為IEEE通訊學門所主導的年度三大盛會之一，另外兩大研討會為ICC（International Conference on Communication）與GLOBECOM（Global Communications Conference）。MILCOM的宗旨係促進全球產、官、學界在通訊領域科技的發展，以提升軍事通訊科技與產品的創新與服務。同時，MILCOM也提供全球通訊科技產業一個最佳的軍事通訊產品的展示平台，讓各國的與會者或採購者能充分地了解最先進的軍事通訊技術與產品。今年，MILCOM 11的主題為「網路—獲得其價值」("Networks ⋯ Attaining the Value")。

貳. 出國過程

今年的 MILCOM 11 大會是在美國馬里蘭州的巴爾地摩市(Baltimore)舉行，會議期程為 11 月 7 日至 11 月 10 日。巴爾地摩市為馬里蘭州的最大城市與文化的中心。其著名的內港(Inner Harbor)曾經是全美國第二大的移民(移入美國)港口與主要的製造中心。11 月 4 日，個人從高雄小港機場出發，途經香港轉機並搭乘國泰航空班機（機票較便宜）直飛美國舊金山機場。不同於去年，這次的運氣較好，因為分到靠走道的位置，可以自由地在飛機上走動，所以整趟 14 小時的航程還算愉快。

由於開會前兩周才知道個人發表論文是被安排在 11 月 9 日的下午，所以先利用 11 月 5 日與 6 日兩天的時間，至舊金山地區拜訪母校「美國海軍研究院」（Naval Postgraduate School）的師友，除了當面請益論文有關事宜外，也討論個人於未來可能的研究議題與方向。

11 月 6 日深夜，由舊金山機場啟程飛往美國東岸。經國芝加哥機場轉機，11 月 7 日中午，班機安全抵達巴爾地摩 BWI 機場。領取托運行李後，個人就直奔詢問櫃台如何用最經濟的方式可以到達下榻的飯店。因為，今年國科會國外差旅的補助僅區區五萬元整，付機票都不夠！所以出門在外，能省則省。最後，決定搭單軌電車前往下榻的飯店。上車後發現，車上都是非洲裔的美國人，很少看到白人。後來問了人才知道，美國的大眾運輸工具通常都是中低收入戶才會搭乘。而圍繞 Baltimore 市郊大部分的區域，由房子的外觀來看，好像也都是中低收入戶的住宅區。曾在美國求學多年的我，第一次在美國搭乘大眾運輸工具的感覺還蠻特別的。

也許是時差的關係吧，到下榻的飯店 check-in 後，整個人就昏沉沉的。想說

躺床上休息一下再去會場完成註冊程序，結果一覺醒來已經是下午六點了。還好，註冊的時間到晚上七點，沖沖忙忙地趕到會場完成註冊後，肚子也餓了。找到一家 Subway，解決了晚餐後就回飯店休息了。夜晚，走在美國陌生大城市的街道上，還不到八點，幾乎所有的店都關了，感覺還蠻冷清的。頓時，開始想念起台灣的夜市與美食。

為了吃大會所提供的免費早餐，11 月 8 日早上七點就趕到會場了。早餐還不錯，有果汁、咖啡、麵包與新鮮水果，可惜沒有熱騰騰的炒蛋和牛奶。塞了三個麵包後，心滿意足地去查看發表論文的場地。為了能順利地發表論文，這一整天幾乎都在不斷地反覆練習。晚上，約了我的博士論文指導教授共進晚餐。席間，除了閒話家常外，也討論一些研究方面的問題。每次與他討論問題時，都能得到新的知識或新的領悟，不得不佩服他的學識淵博，言之有物。

11 月 9 日早上，又練習了幾遍論文的發表。因為下午就輪到個人發表論文了，雖然是老手了，難免還是有點緊張。為了放鬆心情，遂前往大會的展場參觀。與去年不同，今年展場的內部不得照相，所以只好在門外照了一張展場的照片。今年有許多的廠商參展，放眼望去都是赫赫有名的軍火公司。例如，波音、洛克希德馬汀、雷神、Northrop Grumman 等共 260 家廠商參展。由於今年的主題是網路通訊，所以大部分的攤位都展示了與網路通訊相關的新產品與尖端的軍事通訊科技。無論是從單兵到聯合軍種作戰，或從水下到太空，軍事通訊產品的種類包羅萬象。在去年的個人出國報告中，個人也曾建議國內應由相關單位派員來參訪，不知道這項建議有沒有被聽到。如果有的話，來參訪的人員一定會覺得不虛此行。

雖然參觀展場緩和不少內心的忐忑，但還是有點緊張。畢竟，英文不是我們的母語。要在很短的時間內，說清楚複雜的研究成果與解釋複雜的數學公式，實在不是一件簡單的工作。所幸，藉由不斷地練習，順利完成了論文的發表（如圖二至圖五）。會後，有一位聽眾趨前向我索取簡報的內容，並表示對我的研究感到興趣。這位聽眾的名字是 John Chongoushian，他目前任職於 Bae Systems，職銜是 Manager—Advanced link-16 Products Network Systems。

順利完成論文發表後，終於可以放輕鬆坐下來聽別人發表論文。11 月 10 日這一天，聽了幾場與個人研究相關的論文。從這幾場演講中發現，還蠻多人投入 Link-16 系統性能提升的相關研究，而有些論文的創意真的很特別，可提供個人未來研究方向的思考。下午 2 點，抵達 BWI 機場。此時，已經是歸心似箭了。但是運氣很不好遇到了班機故障航班取消的鳥事，所以在 Baltimore BWI 機場旅館多待了一晚。翌日清早，才順利搭機，並於 11 月 12 日晚間 10:30 返抵國門。這次公務出國，實在是獲益良多。很感謝國科會經費的贊助，也非常感謝海軍各級長官的支持。

參. 心得及建議

如同往年，今年 MILCOM 會議全程為期四天。第一天為報到與開幕，而第

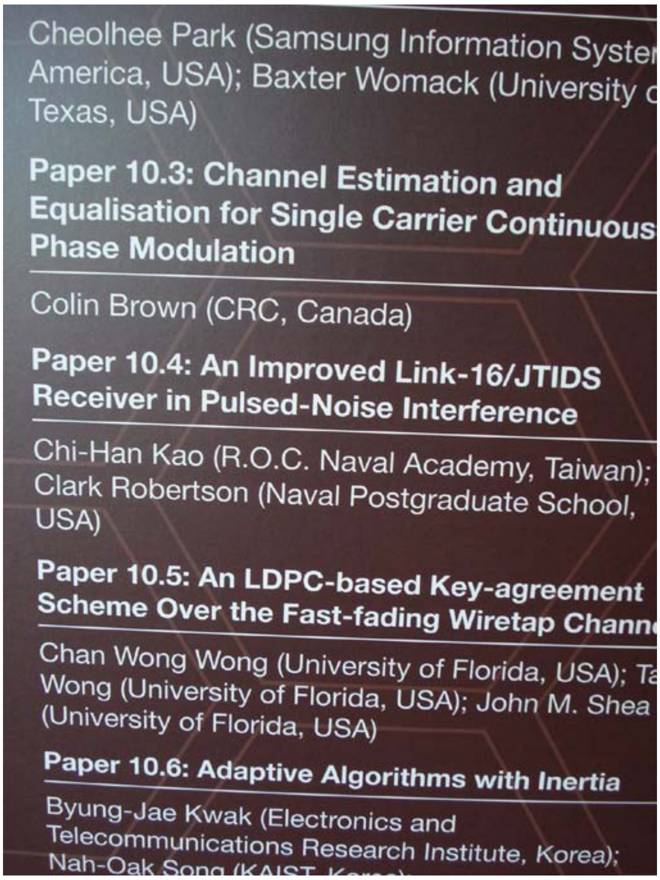
二天到第四天才舉行正式的研討會。MILCOM 特殊的地方，係將研討會區分成「機密」與「非機密」兩部份，分隔兩地舉行。由於個人僅能參加「非機密」的研討會，對「機密」研討會的內容，就不得而知了。今年 MILCOM「非機密」的研討會區分成六大主軸，依序為：WSP（Waveforms and Signal Processing）、NPP（Networking Protocols and Performance）、CSNO（Cyber Security and Network Operations）、MSA（Middlewar Services and Applications），CNS (Communications and Network Systems)，以及 DoD (Department of Defense Programs)。在 WSP 的部份，共有 18 場次的研討會，以及大約 125 篇論文的發表；在 NPP 的部份，共有 15 場次的研討會，以及大約 105 篇論文的發表；在 CSNO 的部份，共有 10 場次的研討會，以及大約 70 篇論文的發表；在 MSA 的部份，共有 6 場次的研討會，以及大約 40 篇論文的發表；在 CNS 的部份，共有 18 場次的研討會，以及大約 120 篇論文的發表；在 DoD 的部份，共有 12 場次的研討會，以及大約 70 篇論文的發表。上述約 500 多篇的論文，係來自全球 17 個國家著名的大學、企業與研究機構。這些國家包括：美國、加拿大、芬蘭、荷蘭、德國、南韓、挪威、中國、希臘、英國、巴西、法國、丹麥、烏克蘭、義大利、葡萄牙，以及台灣。另外，在展場的部份，大約有 260 多家國際著名的企業、廠商或國家級的實驗室參展。例如，Boeing, Lockheed Martin, Raytheon, Northrop Grumman, Aerospace, MITRE, Bae Systems, General Dynamics, SPAWAR 等。上述的數據，足以說明 MILCOM 受到國際社會重視的程度。

這次參加 MILCOM 研討會，最主要的心得為深感自己專業知識的不足。即使個人的名片上印著博士的頭銜，仍發現在本次研討會中有許多領域是個人全然陌生的。例如，Cognitive Radio Networks 與 Wireless Sensor Networks 等最新的網路通訊技術。Cognitive Radio Networks 為雙向型的通訊系統，其特色為發射與接收的參數可自行調整，以增加整個網路系統的效率，並避免相互干擾。Wireless Sensor Networks 則是運用由許多自主式感應器所組成的網路，監控特定區域的溫度、聲音、壓力或震動，以及執行戰場的監視任務等。另外，經過仔細觀察，發現今年的 MILCOM 研討會，僅有個人所發表的乙篇論文來自台灣。然而，中國大陸與南韓卻有許多篇論文在研討會中發表。不知道是不是台灣的產官學界較不重視軍事通訊科技的研發？

綜合上述的觀察，個人建議如下：（一）行政院國科會與國防部應大力主導國內產官學界，共同投入軍事通訊科技的研發。畢竟，國家安全與國防科技的發展，不能假以他人之手。（二）國內相關單位應檢派適員（負責研發或採購人員）參加一年一度的 MILCOM 研討會，以掌握全球軍事通訊技術最新的知識與未來發展趨勢。（三）建議國科會能增加國外差旅的金額，或相關單位（如學校）能提供補助或獎勵，五萬元台幣真的太少了，真的買機票都不夠。最後，還是要感謝國科會經費的贊助，也非常感謝海軍各級長官的支持，讓我有機會代表台灣與海軍軍官學校在國際研討會中發表論文。

圖二、　大會展場入口。

圖三、　個人發表論文會場外之告示牌。



圖四、　個人發表論文會場外之告示牌(局部放大)。

圖五、　個人發表論文現場

論文中文摘要

Link-16戰術資料鏈路通訊系統為北大西洋公約組織成員國、美國及其盟國現役之軍事通訊系統，其主要任務為支援三軍聯合作戰中的「指揮」與「管制」作為。Link-16可提供艦艇、飛機與陸岸設施（如雷達站）間戰術資料的交換，以利戰場指揮官掌握全般戰場圖像，進而有效發揮聯合作戰之戰力。Link-16的通信終端裝置為「聯合戰術資料分配系統」(JTIDS)，其特色包括Reed Solomon (RS)通道編碼、CCSK循環碼鍵移符號調變、MSK最小化鍵移波形調變等技術。本研究係採用錯誤與抹除碼解碼(EED)以及雜訊正規劃結合的MSK(NNC/MSK)解調技術來取代原有之RS錯誤碼解碼與MSK解調技術。由於此研究兼具向前相容性，因此可達成以最經濟的方式來提升Link-16對抗惡意脈波干擾的目標。

錯誤與抹除碼解碼(EED)以及雜訊正規劃結合(NNC)並非最新的通訊技術，但是把這兩種技術合併運用於Link-16接收機，卻是全新的嘗試。為了讓效能分析順利地進行，本研究的假定包括理想的解跳頻與理想的訊息同步。此外，為突顯改良型Link-16/JTIDS接收機的效能，本研究結果會與原系統的效能做客觀公平的比較。根據研究的結果發現，本研究所提出的改良型Link-16/JTIDS接收機在效能上優於原接收機；尤其，當信號雜訊比較強且惡意干擾係以較短的脈波攻擊Link-16系統時，改良型Link-16/JTIDS接收機能讓惡意的脈波干擾幾乎失效。換句話說，惡意的攻擊者只能退而其次使用較溫和的干擾方式，如全頻干擾(Barrage Jamming)。

An Improved Link-16/JTIDS Receiver in Pulsed-Noise Interference

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***Abstract*—Link-16 provides presumably secure and jam-resistant tactical information for land, sea, and air platforms. Its communication terminal, Joint Tactical Information Distribution System (JTIDS), is a hybrid direct-sequence/frequency-hopping spread spectrum system and features Reed-Solomon (RS) codes for channel coding, cyclic code-shift keying (CCSK) for 32-ary baseband symbol modulation, and minimum-shift keying (MSK) for waveform modulation. In this paper, a noise-normalization combining MSK chip demodulator and an errors-and-erasures RS decoder (EED) are proposed in the JTIDS receiver to replace the original MSK chip demodulator and errors-only RS decoder in order to enhance the anti-jam capability of JTIDS. The symbol error rate (SER) performances of the proposed JTIDS receiver are investigated in pulsed-noise interference (PNI) by a combination of analysis and simulation assuming perfect frequency de-hopping, sequence and chip synchronization, and de-scrambling. Given various fraction of time the jammer is on, the SER performances obtained with the proposed JTIDS receiver are compared to those obtained with the original JTIDS receiver. The results show that the proposed JTIDS receiver not only significantly outperforms the original system as the fraction of time the jammer is on is large, but completely eliminates the effect caused by PNI as the fraction of time the jammer is on is small.**

***Index Terms*—Errors-and-erasures decoding, Joint Tactical Information Distribution System, Link-16, noise-normalization combining, pulsed-noise interference.**

I. Introduction

Link-16 provides presumably secure and jam-resistant tactical information for land, sea, and air platforms. Its communication terminal is called Joint Tactical Information Distribution System (JTIDS), a hybrid direct-sequence/frequency-hopping spread spectrum system. JTIDS features Reed-Solomon (RS) codes for channel coding, cyclic code-shift keying (CCSK) for 32-ary baseband symbol modulation, and minimum-shift keying (MSK) for waveform modulation at the chip level [1]. Since the Link-16/JTIDS system will be around for many years to come, the study of potential system improvements against hostile interference is non-trivial.

For the past years, the error rate performances of JTIDS have been analytically investigated in [2]-[8]. Analytic expressions for the symbol error rate (SER) performance of a coherently detected JTIDS-type waveform in additive white Gaussian noise (AWGN) were first seen in [2] for both errors-only RS decoding and errors-and-erasures RS decoding (EED). Its results, however, are based on the overly optimistic assumption that the cross-correlation values of the CCSK symbols are statistically independent. It has been shown in [3] that the cross-correlation values of the CCSK symbol are not statistically independent. Based on the findings of [3], the SER performance of a coherently detected JTIDS-type waveform in Nakagami fading channels and pulsed-noise interference (PNI) was investigated in [4] with errors-only RS decoding and in [5] with EED. The results of [5] showed that EED outperforms errors-only RS decoding when PNI is present. In [6], the SER performance of a coherently detected JTIDS-type waveform with noise-normalization combining (NNC) in PNI is analyzed. Its results show that a JTIDS receiver with NNC outperforms the original JTIDS receiver when PNI is present. Unlike [2]-[6], a JTIDS-compatible waveform which uses 32-ary orthogonal signaling with 32-chip Walsh function to replace CCSK and MSK is proposed in [7]. The bit error rate (BER) performance of the compatible waveform in PNI is evaluated in [7] and [8] for errors-only RS decoding and EED, respectively.

To enhance the anti-jam capability of JTIDS, in this paper a NNC/MSK chip demodulator and an errors-and-erasures RS decoder are assumed in the JTIDS receiver to replace the original MSK chip demodulator and errors-only RS decoder (see Figure 1). The SER performances of the proposed JTIDS receiver are then evaluated in both AWGN and PNI by a combination of analysis and simulation assuming perfect frequency de-hopping, sequence and chip synchronization, and de-scrambling. Moreover, maximum-likelihood chip detection is assumed rather than maximum-likelihood sequence detection since according to [1] the former represents a more practical assumption for the JTIDS signal.The rest of this paper is organized as follows. The system model of the proposed JTIDS receiver is introduced in Section II. The performance analyses of the proposed JTIDS receiver over AWGN and PNI are discussed in Section III. Numerical results are presented in Section IV, and the major findings and contributions of this paper are summarized in the last section.

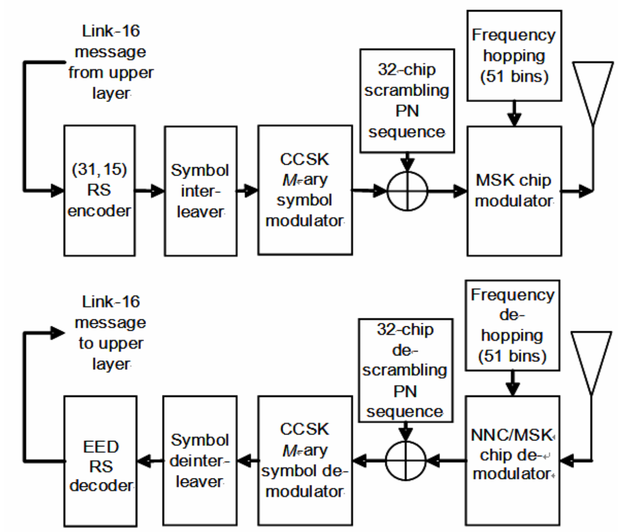

Fig. 1. Major block diagram of the proposed JTIDS transceiver (after [1]).

II. System Model Description

A. JTIDS Transmitter

The JTIDS transmitter (the top branch of Figure 1) consists of a RS channel encoder, a symbol interleaver, a 32-ary CCSK baseband symbol modulator, a 32-chip sequence scrambler, a frequency-hopping circuit, and a MSK chip level modulator. In other words, the major processes involved to generate a JTIDS waveform includes bit-to-symbol mapping, RS encoding, pseudo-random symbols interleaving, 32-ary CCSK baseband symbol modulation (each 5-bit coded symbol is converted into a 32-chip nonorthogonal sequence), PN sequence scrambling, MSK waveform modulation on a chip-by-chip basis, and frequency-hopping. After up-conversion, the signal is amplified, filtered, and transmitted over the channel. Note that Link-16 data may be transmitted as either single or double pulses (each pulse has a duration of 6.4 μsec) depending the operation mode of JTIDS. In Normal mode, Link-16 data are transmitted as double pulses; that is, each symbol is transmitted twice on different carrier frequencies [1]. In this case, JTIDS may be viewed as a hybrid direct-sequence/fast frequency-hopping spread spectrum system with a sequential diversity of two. To facilitate the performance analyses, the Normal mode of JTIDS is assumed throughout this paper.

B. The Proposed JTIDS Receiver

The major components of the proposed JTIDS receiver (the bottom branch of Figure 1) are almost the same as the original JTIDS receiver except the MSK chip demodulator and the errors-only RS decoder are replaced by a NNC/MSK chip demodulator and an EED RS decoder, respectively. Note that the JTIDS waveform is noncoherently detected at the chip level due to the fast hopping rate. In this paper a coherently detected JTIDS waveform is evaluated to ascertain the performance possible if coherent demodulation were practical. The block diagram of the proposed NNC/MSK chip demodulator is illustrated in Figure 2, where the input $r(t)$ represents the received noisy JTIDS signal, and the output $\tilde{s}$ represents the demodulated 32-chip sequence ready for de-scrambling. In Figure 2, we assume that the noise measurement circuit can accurately measure the noise power of each chip. The measured noise power is used to normalize the sampled output of the correlator for each chip of the first JTIDS pulse prior to soft-decision (SD) combing with each chip of the second JTIDS pulse in order to obtain the decision statistics. Since jammed chips are de-emphasized with respect to unjammed chips, this procedure minimizes the influence of jammed chips on the overall decision statistics.

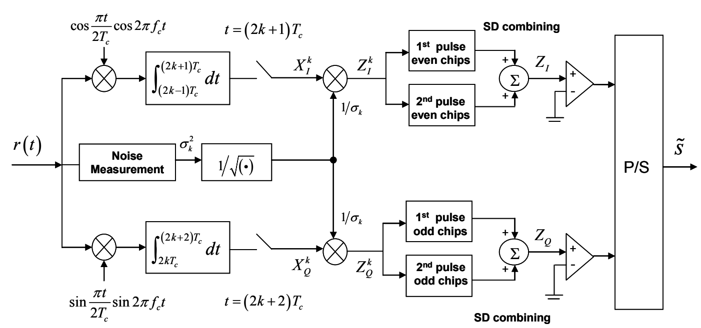

Fig. 2. The proposed coherent NNC/MSK chip demodulator.

After NNC/MSK chip demodulation and de-scrambling, each 5-bit channel symbol is recovered by a 32-ary CCSK baseband symbol demodulator shown in Figure 1. The determination of which channel symbol was received is accomplished by computing the cross-correlation between the de-scrambled 32-chip sequence and the 32 possible CCSK sequences. The decision is made by choosing the channel symbol with the largest cross-correlation value. Since EED is assumed, the CCSK symbol demodulator may yield thirty-three possible outputs corresponding to symbol 0, 1…, 31, and symbol erasure. Note that a channel symbol is erased when the CCSK symbol demodulator cannot make a decision as to which channel symbol was received with sufficient confidence, which occurs when the largest CCSK cross-correlation value is less than the preset erasure threshold. More details about the 32-ary CCSK baseband symbol demodulation are discussed in [3]. After symbol de-interleaving, the channel symbols are decoded by an EED RS decoder. If the decoding is successful, the information symbols are recovered.

III. Performance Analyses

In order to compare the SER performance of the proposed JTIDS receiver to that of the original JTIDS receiver, the performance analyses are divided into three subsections: the original JTIDS receiver in PNI, the modified (original JTIDS receiver with EED) JTIDS receiver in PNI, and the proposed JTIDS receiver in PNI.

A. Performance of the original JTIDS Receiver in PNI

To investigate the SER performance of JTIDS in PNI, analytic expressions at the output of MSK chip demodulator, CCSK symbol demodulator, and RS decoder are required. For a linear, non-binary block code such as RS code that can correct up to t symbol errors in every block of n symbols, the probability of symbol error is given by [9]

$$P_S = \frac{1}{n}\sum_{i=t+1}^{n} i \binom{n}{i} p_s^i \left(1-p_s\right)^{n-i}, \qquad (1)$$

where i represents the number of symbol errors, and p_s is the average probability of channel symbol error at the output of the CCSK symbol demodulator. For JTIDS with the double-pulse mode in both AWGN and PNI, the average probability of channel symbol error is given by

$$p_s = \sum_{\ell=0}^{2} \binom{2}{\ell} \rho^{\ell} \left(1-\rho\right)^{2-\ell} p_{s|\ell}, \qquad (2)$$

where $\ell = 0,1,2$ denotes the number of pulses are affected by PNI, $0 < \rho \le 1$ represents the fraction of time the PNI is turned on, and $p_{s|\ell}$ is the conditional probability of channel symbol error given that ℓ pulses are affected by PNI. Note that $\rho = 1$ implies barrage noise interference (BNI). From total probability theorem, the conditional probability of channel symbol error $p_{s|\ell}$ is given by

$$p_{s|\ell} = \sum_{j=0}^{32} \zeta_j \binom{32}{j} p_{c|\ell}^j \left(1-p_{c|\ell}\right)^{32-j}, \qquad (3)$$

where ζ_j are conditional probabilities of channel symbol error given that j chip errors have occurred in the de-scrambled 32-chip sequence, and $p_{c|\ell}$ is the conditional probability of channel chip error given that ℓ pulses are affected by PNI. The values of ζ_j were obtained both analytically (denoted as ζ_{UB_j}) and by Monte Carlo simulation (denoted as ζ_{SIM_j}) in [3]. For a fair comparison between the original and the proposed systems, ζ_{SIM_j} is used in this paper to evaluate the SER performance of the original JTIDS system. For the purpose of convenience, the values of ζ_{UB_j} and ζ_{SIM_j} are reproduced here in Table I.

TABLE I PROBABILITIES OF SYMBOL ERROR GIVEN THAT j CHIP ERRORS HAS OCCURRED IN THE DE-SCRAMBLED 32-CHIP SEQUENCE: ANALYTIC RESULT VERSUS MONTE CARLO SIMULATION (FROM [3]).

j	ζ_{UB_j}	ζ_{SIM_j}
0	0	0
⋮	⋮	⋮
6	0	0
7	0.0015	0.0015
8	0.0207	0.0194
9	0.1166	0.1126
10	0.4187	0.3669
11	1.0	0.7093
12	1.0	0.9351
13	1.0	0.9953
14	1.0	1.0
⋮	⋮	⋮
32	1.0	1.0

When AWGN and PNI are statistically independent, PNI may be modeled as Gaussian noise. Furthermore, when a coherent matched filter or correlator is used to recover the binary data, MSK has the same performance as BPSK, QPSK, and offset QPSK [10]. Thus, when coherent MSK demodulation is practical, the conditional probability of channel chip error $p_{c|\ell}$ is given by

$$p_{c|\ell} = Q\left(\sqrt{\frac{0.625 r L E_{b'}}{N_0 + \left(\ell N_I / L\rho\right)}}\right), \qquad (4)$$

where $r = k/n$ is the code rate, $L = 2$ for the double-pulse mode, $E_{b'}$ represents the average energy per bit per pulse, N_0 denotes the one-sided AWGN power spectral density, and N_I is the one-sided power spectral density of PNI. Note that in (4) we use the fact that for JTIDS, $E_s = 5E_b = 32E_c$ and $E_b = LE_{b'}$. Now, using (2) through (4) in (1) with $r = 15/31$, $L = 2$, $\ell = 0,1,2$, the values of ζ_{UB_j} from Table I, and various ρ, we obtain the SER performances of the original JTIDS receiver in both AWGN and PNI.

B. Performance of the modified JTIDS Receiver in PNI

In this subsection the SER performance of the modified JTIDS receiver in PNI is investigated. The *modified* receiver is referred to as the original JTIDS receiver with EED. As the previous subsection, several analytic expressions are required to investigate the SER performance of the modified system. When EED is applied, the block error probability of a RS code that can up to t symbol errors and/or ε symbol erasures in every block of n symbols is given by

$$P_E = \sum_{i=t+1}^{n} \binom{n}{i} p_s^i \sum_{\varepsilon=0}^{n-i} \binom{n-i}{\varepsilon} p_e^{\varepsilon} p_o^{n-i-\varepsilon} + \sum_{i=0}^{t} \binom{n}{i} p_s^i \sum_{\varepsilon=d_{\min}-2i}^{n-i} \binom{n-i}{\varepsilon} p_e^{\varepsilon} p_o^{n-i-\varepsilon}, \qquad (5)$$

where p_s is the average probability of channel symbol error, p_e denotes the average probability of channel symbol erasure, p_o represents the average probability of channel symbol correct, and $d_{\min}$ is the minimum Hamming distance. In (5) the first term on the right-hand side is obtained from the fact that a block error occurs when $i > t$ regardless of the number of the symbol erasures, and the second term on the right-hand side is obtained when the number of symbol erasures $\varepsilon > d_{\min} - 2i - 1$ even when $i \le t$. Next, given the probability of block error, the probability of symbol error P_S is given by

$$P_S = \Pr\left\{\text{symbol error} \middle| \text{block error}\right\} P_E. \qquad (6)$$

When a total of i symbol errors and ε symbol erasures result in a block error, the conditional probability of symbol error is approximately [11]

$$\Pr\left\{\text{symbol error} \middle| \text{block error}\right\} \approx \frac{i+\varepsilon}{n}. \qquad (7)$$

Now, substituting (5) and (7) into (6), we obtain

$$P_S \approx \frac{1}{n}\left[\sum_{i=t+1}^{n}\binom{n}{i}p_s^i\sum_{\varepsilon=0}^{n-i}(i+\varepsilon)\binom{n-i}{\varepsilon}p_e^{\varepsilon}p_o^{n-i-\varepsilon} + \sum_{i=0}^{t}\binom{n}{i}p_s^i\sum_{\varepsilon=d_{\min}-2i}^{n-i}(i+\varepsilon)\binom{n-i}{\varepsilon}p_e^{\varepsilon}p_o^{n-i-\varepsilon}\right]. \quad (8)$$

Note that for JTIDS with the double-pulse mode in both AWGN and PNI, the average probability of channel symbol error p_s is the same as that given in (2) since it is independent on the types of forward error correction (FEC) codes being used; however, the conditional probability of channel symbol error given in (3) needs to be modified as

$$p_{s|\ell} = \sum_{j=0}^{32}\zeta_{s_j}\binom{32}{j}p_{c|\ell}^{j}\left(1-p_{c|\ell}\right)^{32-j}, \quad (9)$$

where ζ_{s_j} are the conditional probabilities of channel symbol error given that j chip errors have occurred in the de-scrambled 32-chip sequence. Similarly, the average probability of channel symbol erasure is given by

$$p_e = \sum_{\ell=0}^{2}\binom{2}{\ell}\rho^{\ell}\left(1-\rho\right)^{2-\ell}p_{e|\ell}, \quad (10)$$

and the conditional probability of channel symbol erasure $p_{e|\ell}$ given that ℓ pulses are affected by PNI is

$$p_{e|\ell} = \sum_{j=0}^{32}\zeta_{e_j}\binom{32}{j}p_{c|\ell}^{j}\left(1-p_{c|\ell}\right)^{32-j}, \quad (11)$$

where ζ_{e_j} represents the conditional probabilities of channel symbol erasure given that j chip errors have occurred in the de-scrambled 32-chip sequence. Finally, the average probability of channel symbol correct is obtained as

$$p_o = \sum_{\ell=0}^{2}\binom{2}{\ell}\rho^{\ell}\left(1-\rho\right)^{2-\ell}p_{o|\ell}, \quad (12)$$

and the conditional probability of channel symbol correct $p_{o|\ell}$ given that ℓ pulses are affected by PNI is given by

$$p_{o|\ell} = \sum_{j=0}^{32}\zeta_{o_j}\binom{32}{j}p_{c|\ell}^{j}\left(1-p_{c|\ell}\right)^{32-j}, \quad (13)$$

where ζ_{o_j} are the conditional probabilities of channel symbol correct given that j chip errors have occurred in the de-scrambled 32-chip sequence. Note that the values of ζ_{s_j}, ζ_{e_j}, and ζ_{o_j} were obtained by Monte Carlo simulation based on an obtained optimal erasure threshold $T_{opt} = 14$ [5]. For the purpose of convenience, the values of ζ_{s_j}, ζ_{e_j}, and ζ_{o_j} for $0 \le j \le 32$ are reproduced here in Table II. Note that the conditional probability of channel chip error $p_{c|\ell}$ shown in (9), (11), and (13) are the same as that given in (4) since it is independent on the types of FEC code being used. Now, substituting (4) and (9) through (13) into (8) with $r = 15/31$, $L = 2$, $\ell = 0, 1, 2$, and the values of ζ_{s_j}, ζ_{e_j}, ζ_{o_j} from Table II with various ρ, we obtain the SER performances of the modified JTIDS receiver in both AWGN and PNI.

TABLE II SIMULATION RESULTS FOR ζ_{s_j}, ζ_{e_j}, ζ_{o_j} WHEN $T_{opt} = 14$.

j	ζ_{s_j}	ζ_{e_j}	ζ_{o_j}
0	0	0	1
⋮	⋮	⋮	⋮
6	0	0	1
7	0.0018	0	0.9982
8	0.0194	0	0.9806
9	0.1116	0	0.8884
10	0.0772	0.9228	0
11	0.3033	0.6967	0
12	0.1217	0.8783	0
13	0.3715	0.6285	0
14	0.1624	0.8376	0
15	0.4313	0.5687	0
16	0.1711	0.8289	0
17	0.4429	0.5571	0
18	0.1876	0.8124	0
19	0.4339	0.5661	0
20	0.1675	0.8325	0
21	0.4032	0.5968	0
22	0.1331	0.8669	0
23	0.3263	0.6737	0
24	0.0837	0.9163	0
25	0.2129	0.7871	0
26	0.0311	0.9689	0
27	0.0981	0.9019	0
28	0	1	0
⋮	⋮	⋮	⋮
32	1	0	0

C. *Performance of the Proposed JTIDS Receiver in PNI*

For the proposed receiver, a NNC/MSK chip demodulator and an errors-and-erasures RS decoder (EED) are assumed in the receiver to replace the original MSK chip demodulator and errors-only RS decoder, respectively. In this case, (8) through (13) are still valid for evaluating the SER performance of the proposed JTIDS receiver in both AWGN and PNI, but the conditional probability of channel chip error $p_{c|\ell}$ given in (4) needs to be modified due to the additional noise-normalization diversity combing circuit.

The NNC/MSK chip demodulator is illustrated in Figure 2, where the top branch is the in-phase channel and the bottom branch is the quadrature channel. When PNI is present, it can be shown that the random variable X_I^k that models the output of the correlator is a Gaussian random variable with a probability density function (PDF)

$$f_{X_I^k}\left(x_I^k\right) = \frac{1}{\sqrt{2\pi}\sigma_k}\exp\left[-\left(x_I^k - \overline{X_I^k}\right)^2 \Big/ 2\sigma_k^2\right], \quad (14)$$

where $k = 1 \text{ or } 2$ denotes the chip coming from the first or the second JTIDS pulse. The random variable X_I^k has a mean of $\overline{X_1^k} = \pm\sqrt{2}A_c$ representing a binary chip 1 or 0, and a variance of $\sigma_k^2 = \left(N_0 + N_I/\rho\right)/T_c$. After noise-normalization, we obtain another random variable $Z_I^k = X_I^k/\sigma_k$. Next, applying single random variable transformation, we obtain the PDF of Z_I^k

$$f_{Z_I^k}\left(z_I^k\right)=\frac{1}{\sqrt{2\pi}}\exp\left[-\left(z_I^k-\overline{Z_I^k}\right)^2\Big/2\right], \qquad (15)$$

which shows that Z_I^k is also a Gaussian random variable with a mean $\overline{Z_I^k}=\overline{X_I^k}\big/\sigma_k$ and unity variance. After buffering, each even chip of the first JTIDS pulse is soft-decision combined with each even chip of the second pulse to obtain the decision statistics

$$Z_I=\sum_{k=1}^{2}Z_I^k\,. \qquad (16)$$

Since sum of Gaussian random variables yields another Gaussian random variable, the decision statistics Z_I is still Gaussian with a mean

$$\overline{Z_I}=\sum_{k=1}^{2}\overline{Z_I^k}\,, \qquad (17)$$

and variance

$$\sigma_{Z_I}^2=\sum_{k=1}^{2}\sigma_{Z_I^k}^2=2\,. \qquad (18)$$

When ℓ pulses are affected by PNI, the mean of the decision statistics shown in (17) becomes

$$\overline{Z_I}=\pm\sqrt{2}A_c\left(\frac{\ell}{\sqrt{N_0+N_I/\rho}}+\frac{2-\ell}{\sqrt{N_0}}\right)\sqrt{T_c}\;, \qquad (19)$$

where $\ell=0,1,2$. Squaring both sides of (19), we obtain

$$\overline{Z_I}^2=2E_c\left(\frac{\ell}{\sqrt{N_0+N_I/\rho}}+\frac{2-\ell}{\sqrt{N_0}}\right)^2, \qquad (20)$$

where $E_c=A_c^2T_c$. When coherent detection is practical, the probability of chip error of a coherently detected NNC/MSK chip demodulator in both AWGN and PNI is given by

$$P_c=Q\left(\sqrt{\frac{\overline{Z_I}^2}{\sigma_{Z_I}^2}}\right). \qquad (21)$$

Substituting (18) and (20) into (21), we obtain the conditional probability of chip error of a coherently detected NNC/MSK chip demodulator given that ℓ pulses are affected by PNI as

$$P_{c|\ell}=Q\left(\sqrt{E_c\left(\frac{\ell}{\sqrt{N_0+N_I/\rho}}+\frac{2-\ell}{\sqrt{N_0}}\right)^2}\right). \qquad (22)$$

When FEC coding is applied and when the double-pulse mode is chosen for JTIDS, the conditional probability of channel chip error is given by

$$p_{c|\ell}=Q\left(\sqrt{0.3125rE_{b'}\left(\frac{\ell}{\sqrt{N_0+N_I/\rho}}+\frac{2-\ell}{\sqrt{N_0}}\right)^2}\right), \qquad (23)$$

where r is the code rate. Note that similar result is obtained for the quadrature channel. Now, using (9) through (13) and (23) in (8) with $r=15/31$, $\ell=0,1,2$, and the values of ζ_{s_j}, ζ_{e_j}, ζ_{o_j} from Table II with various ρ, we obtain the SER performance for the proposed JTIDS receiver in both AWGN and PNI.

IV. NUMERICAL RESULTS

Due to the space constraint, only two signal-to-noise ratio (SNR) cases are considered in this paper for presenting the numerical results. The first case is given $E_{b'}/N_0=3$ dB for the low SNR scenario, whereas the second is given $E_{b'}/N_0=10$ dB for the normal SNR scenario. Given $E_{b'}/N_0=3$ dB, the SER performance of the proposed JTIDS receiver in both AWGN and PNI is shown in Figure 3 for $\rho=0.75$ and $\rho=0.25$ (PNI is turned on for 75% and 25% of the time), respectively. In order to compare the SER performance of the proposed JTIDS receiver to the modified and the original JTIDS receiver, all three results are shown in the same figure. From Figure 3, two observations can be made. First, given the same value of ρ, the proposed receiver outperforms the other two receivers. For example, given $\rho=0.75$ at $P_s=10^{-5}$, the proposed receiver outperforms the modified receiver by 0.2 dB and outperforms the original receiver by 1.5 dB. Second, the proposed JTIDS receiver outperforms the other two receivers by a greater margin as the value of ρ decreases. For example given $\rho=0.25$ at $P_s=10^{-5}$, the proposed receiver outperforms the modified receiver by 3.3 dB and outperforms the original receiver by 5 dB.

Next, given $E_{b'}/N_0=10$ dB, the numerical results are shown in Figure 4. Several observations can be made. First, as expected, the SER performance improves as the value of $E_{b'}/N_0$ increases. For example, for the modified JTIDS receiver the required $E_{b'}/N_I$ is reduced to 1.4 dB (a reduction of 3 dB if compared to Figure 3) at $P_s=10^{-5}$. Second, given the same ρ, the proposed JTIDS receiver still outperforms the other two receivers, whether $E_{b'}/N_0$ is large or small. Lastly, noting the trends as ρ decreases and $E_{b'}/N_0$ increases, for sufficiently large value of $E_{b'}/N_0$, the proposed JTIDS receiver completely eliminates the effect of PNI.

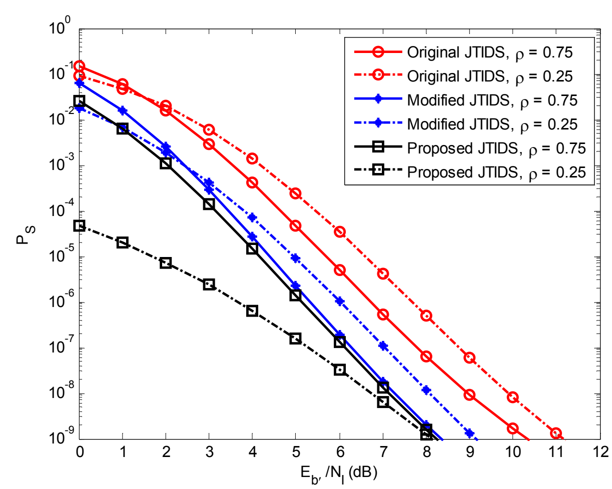

Fig. 3. SER performances of the improved JTIDS receivers versus the original JTIDS receiver in both AWGN and PNI, where $E_{b'}/N_0=3$ dB.

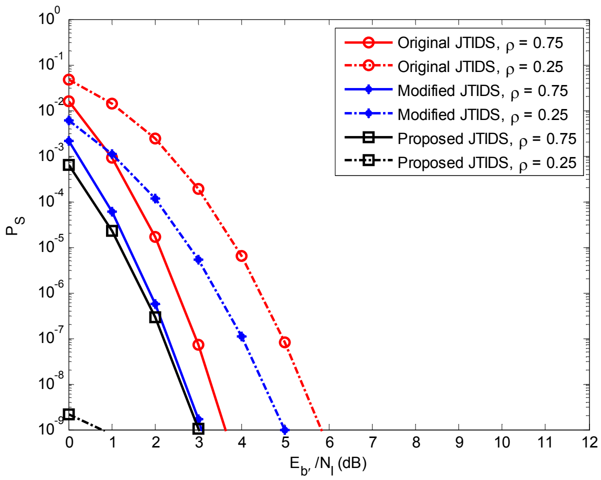

Fig. 4. SER performances of the improved JTIDS receivers versus the original JTIDS receiver in both AWGN and PNI, where $E_{b'}/N_0 = 10$ dB.

V. Conclusion

In this paper, an improved JTIDS receiver was proposed and its SER performances in both AWGN and various PNI are investigated. The proposed receiver utilizes a NNC/MSK chip demodulator and an EED RS decoder to replace the original MSK chip demodulator and errors-only RS decoder. Neither NNC nor EED is new, but the idea of combining both NNC and EED in the JTIDS receiver to enhance its anti-jam capability has not been presented before. The results show that the proposed receiver not only significantly outperforms the original JTIDS receiver when PNI is present, but also completely eliminates the effect of PNI when both the fraction of time the PNI is on is small and the signal-to-noise ratio is large. In an anti-jam scenario, this is the best we can hope for since the jammer is forced to abandon PNI and adopt a benign jamming strategy such as BNI. Since Link-16 will be around for many years to come, the study of potential system improvements for JTIDS against hostile jamming is non-trivial.

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