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사물지능 통신을 위한 고효율 저복잡도 대역 확산 알로하 기법

노 홍 준◆, 박 형 원*, 임 재 성°

High-Efficiency and Low-Complexity Spread Spectrum ALOHA for Machine-to-Machine Communications

Hong-jun Noh◆, Hyung-won Park*, Jae-sung Lim°

요 약

본 논문은 동시 전송 가능한 사물지능 통신 트래픽의 수를 늘리기 위하여 doubly truncated cyclic code shift keying (DTCCSK)을 활용한 대역 확산 알로하 기법을 제안한다. 제안하는 DTCCSK는 정사각형으로 표시되는 cyclic code shift keying 코드셋의 우측과 하단을 절삭함으로써 생성 가능하며, spreading factor와 심볼 길이를 자유롭게 설계할 수 있는 특징을 가진다. 또한 DTCCSK는 대역 확산 알로하의 변복조 기법으로 주로 사용되는 direct sequence 보다 높은 주파수 효율을 보이면서도 M-ary 시그널링 기법에 비해서는 낮은 구현 복잡도로 구현이 가능하다. 본 논문은 사물지능 통신을 위해 대역 확산 알로하를 채택한 S-band mobile interactive multimedia 표준을 참고하여 시뮬레이션 환경을 구성하였고 DTCCSK의 성능을 검증하였다.

Key Words : M2M Communication, Satellite Networks, Spread Spectrum ALOHA, Cyclic Code Shift Keying, Random Access

ABSTRACT

To improve the number of simultaneous transmissions of machine-to-machine traffic in a spread spectrum ALOHA channel, we propose a new spreading technique called doubly truncated cyclic code shift keying (DTCCSK). By truncating the codeset of cyclic code shift keying, DTCCSK freely adjusts the spreading factor and the symbol length. As a result, DTCCSK exhibits both a high spectral efficiency of M-ary signaling and low implementation complexity of a direct sequence.

Ⅰ. Introduction

The services offered by next-generation satellite networks (SATNETs) will extend to machine-to-machine (M2M) applications such as mobile messaging, supervisory control and data acquisition, disaster response, and telemetry[1]. The traffic type can be characterized by low volumes of data and dynamic occurrences from a large number of devices[2]. Under this traffic condition, random access (RA) is more robust than traditionally used demand assignment multiple access because RA has

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◆ First Author : LIG Nex1 C4I R&D Laboratory, hongjun.noh@lignex1.com, 정회원
° Corresponding Author : Ajou University Department of Computer Engineering, jaslim@ajou.ac.kr, 종신회원
* LIG넥스원 C4I연구소 위성통신체계PM, hyungwon.park@lignex1.com

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no control overhead to assign satellite resources to a specific user[3,4].

In SATNETs, because of the long propagation delay, carrier-sensing-based RA schemes are ineffective; therefore, ALOHA-based RA schemes are mainly used. However, the throughput of pure ALOHA is too low (approximately 0.18 packets per packet duration) to transmit user traffic. Slotted ALOHA, which doubles the throughput of pure ALOHA, is also not suitable for M2M applications because its synchronization overhead is a big burden to low-powered M2M devices, especially mobile devices[5]. Given these conditions, spread spectrum aloha (SSA)[6] can be a good solution. SSA does not need any synchronization process between terminals and colliding packets can be restored owing to a spreading gain. Because of these advantages, the S-band mobile interactive multimedia (S-MIM) standard has adopted an SSA-based RA scheme to provide ubiquitous messaging services between M2M devices[7].

For M2M communications, the number of simultaneous transmissions is a more important performance factor than the data rate of each transmission because M2M traffic has small volumes of data whose traffic occurrence frequency dynamically changes. To increase the number of simultaneous transmissions, we need to increase both spreading factor (SF) and spectral efficiency (bits/s/Hz) where SF is the ratio between the transmission bandwidth and the original bandwidth. Conventional SSA systems use a direct sequence (DS) as a spread-spectrum technique, which spreads one bit to multiple chips. Because the demodulator structure of DS is simple, DS/SSA can easily increase SF. Because the demodulator of DS/SSA requires one demodulator, DS/SSA can easily increase SF. However, DS/SSA is known to have low spectral efficiency. As another spreading technique, M-ary signaling (MOS) can be used for SSA. The spectral efficiency of MOS/SSA is higher than that of DS/SSA because the bit error rate of the MOS/SSA system can approach the Shannon limit by increasing the number of orthogonal sequences[8]. However, MOS/SSA also has a problem in that the demodulator of MOS/SSA requires M correlators. This complexity of MOS/SSA restricts SF to low values.

In this paper, we propose a new spreading technique for SSA. We call this new technique doubly truncated cyclic code shift keying (DTCCSK). DTCCSK is based on CCSK[9] and has high spectral efficiency and low implementation complexity. By truncating the CCSK codeset, DTCCSK/SSA freely adjusts SF and the symbol length. Simulation results verify that DTCCSK/SSA outperforms a system using DS/SSA in terms of packet loss ratio (PLR), throughput, and spectral efficiency. Simulation results also show that the spectral efficiency of DTCCSK/SSA approaches that of MOS/SSA under similar values of SF.

Ⅱ. System Model Description

To design a system model, we consider a network in which a number of M2M devices transmit packets to an M2M gateway via a satellite link. The satellite channel under consideration features fully asynchronous random access, and a spread-spectrum communication similar to the random access channel of S-MIM[7]. Fig. 1 depicts the system model and the transmitter configuration. Transmitted signals from M2M devices arrive at the M2M gateway at different times, because of different packet generation times, and propagation delays. Each transmitted signal undergoes independent fading, and AWGN is added to the summed signals at the

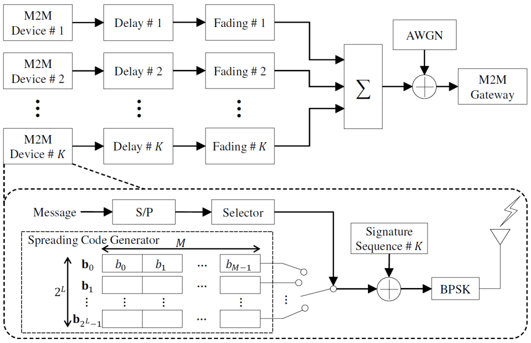


Fig. 1. System model and transmitter configuration

gateway.

In the transmitter, a packet is divided into symbols of L bits each by the serial-to-parallel converter. Then the spreading code generator selects one spreading code from a spreading codeset based on the input symbol. We define $\mathbf{b}_n$, and M as the nth spreading code, and the length of $\mathbf{b}$, respectively. Therefore, SF can be calculated as follows:

$$SF = M/L. \tag{1}$$

In a DS/SSA system, $L = 1$, $\mathbf{b}_1 = -\mathbf{b}_0$, and $SF = M$. After spreading, a signature sequence is added to distinguish the device at a receiver. In this paper, we do not consider forward error correction coding so that we can check the effect of the spreading technique alone. Binary phase shift keying (BPSK) is used as a modulation scheme. At the receiver side, the demodulator detects each packet using preamble detection. This procedure is described in detail in Section Ⅳ of [1].

Ⅲ. Proposed Scheme

In this section, we describe a new spread-spectrum technique for SSA with low implementation complexity and high spectral efficiency. Because the proposed scheme, called DTCCSK, is designed based on CCSK, we provide a brief overview of the characteristics of CCSK before describing DTCCSK.

3.1 Cyclic Code Shift Keying

CCSK is a form of M-ary signaling where a symbol of L bits is converted into M chips and $M = 2^{L}$[9]. Generally, the fundamental code of CCSK, $\mathbf{b}_0$, is generated using a modified maximal length sequence (MMLS) that has a good autocorrelation property and a length of powers of 2. As can be inferred from the name of CCSK, an nth code, $\mathbf{b}_n$, is generated by the nth cyclic shift of $\mathbf{b}_0$, where n is the value of an L-bit symbol ($n = 0, 1, \dots, 2^{L-1}$). Therefore, $\mathbf{b}_0$ and $\mathbf{b}_n$ can be represented as row vectors as follows:

$$\mathbf{b}_0 = (b_0, b_1, \dots, b_{M-1}), \tag{2}$$

$$\begin{aligned}\mathbf{b}_n = (&b_{M-n}, b_{M-n+1}, \dots, b_{M-1}, b_0, \\ &\dots, b_{M-n-1}),\end{aligned} \tag{3}$$

where $b_m = \pm 1$. We call the square matrix whose nth row vector is $\mathbf{b}_0$ a CCSK codeset. Because of the good autocorrelation property of $\mathbf{b}_0$, spreading codes in the CCSK codeset are semi-orthogonal with each other.

The demodulation of CCSK is performed by computing the cyclic correlation of the received signal with $\mathbf{b}_0$. The advantage of CCSK is that the cyclic correlation is easily implemented by a fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) operation. Let $\mathbf{r}$ be the sampled received signal at the baseband detector. Then, the result of the cyclic correlation of $\mathbf{r}$ with $\mathbf{b}_0$ is represented as a row vector $\mathbf{S}$ as follows[9]:

$$\begin{aligned}\mathbf{S} &= \left|\mathrm{IFFT}(\mathrm{FFT}(\mathbf{r}) \times \mathrm{FFT}^*(\mathbf{b}_0))\right| \\ &= (S_0, S_1, \dots, S_{M-1}),\end{aligned} \tag{4}$$

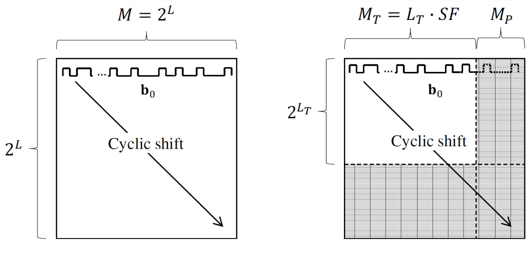
where x^* is the complex conjugate of x, and S_n is the value of the cross-correlation of $\mathbf{r}$ with $\mathbf{b}_n$. The bits corresponding to the nth symbol are selected as output, if $\max\{\mathbf{S}\} = S_n$.

As the length of code increases, the performance of CCSK is similar to that of MOS. However, MOS and CCSK cannot support various SFs. In other words, the values of an SF are restricted to specific values. For example, when the values of L are 7, 8, 9, and 10, the values of SF are 18.3, 32, 56.9, and 104.4, respectively. On the other hand, using DS, a system designer can easily adopt various SFs such as 50, 70, and 100. Therefore, this restriction of MOS and CCSK disrupts the design of a freely adjustable system.

3.2 Doubly Truncated Cyclic Code Shift Keying

In this section, we propose a new spread-spectrum technique, called DTCCSK, to enhance the aggregated throughput of the RA channel. Because a DTCCSK codeset is constructed based on a CCSK codeset, DTCCSK has the same advantages of CCSK, such as low complexity and high spectral efficiency. Unlike CCSK, DTCCSK can support various values of SFs even larger than 2 to the power of the symbol length.

Fig. 2(a) and 2(b) show the codesets of CCSK and DTCCSK, respectively. As shown in Fig. 2(a), the CCSK codeset forms a square shape because the length of code is the same as the number of values of the L-bit symbol, i.e., $M = 2^L$. The DTCCSK codeset is made by simply truncating the right side and the bottom side of the CCSK codeset, as shown in Fig. 2(b). From now on, we will call the truncation of the right side and the truncation of the bottom side as a vertical truncation and a horizontal truncation, respectively. We can adjust SF to a specific value by using both truncations. The vertical truncation increases the data rate and reduces the required bandwidth because the length of a spreading code is reduced. Let M_T be the remaining code length after vertical truncation. At the receiver, the truncated part is padded by zeros of M_P $(= M - M_T)$ chips in order to keep the length of two powers of L. If we use the vertical truncation only, to create the DTCCSK codeset with a specific value of SF, we need the CCSK codeset whose L satisfies the following condition:



(a) CCSK code set (b) DTCCSK code set

Fig. 2. Comparison of CCSK and DTCCSK codesets

$$2^L / L > SF \tag{5}$$

For example, if $SF = 200$, the minimum values of L and M are 12 and 4096, respectively; and M_T and M_P are 2400 and 1696, respectively. Owing to the large size of the zero padding, according to the values of SF, the structures of the transmitter and the receiver can be inefficient when we use the vertical truncation only.

The horizontal truncation can redeem this inefficiency of the vertical truncation. The horizontal truncation reduces the number of bits in a DTCCSK symbol. Let L_T be the reduced number of bits in the DTCCSK symbol. Then, given SF, $M_T = L_T \cdot SF$, and the number of codes in the DTCCSK codeset is 2^{L_T}. At the receiver, we only use the first 2^{L_T} elements of S in (4) to detect the DTCCSK symbol. The main advantage of the horizontal truncation is that we do not need to follow the condition of (5). Given SF and L_T, the new condition for the base CCSK codeset is as follows:

$$L_T \le L, M_T \le 2^L, \tag{6}$$

to construct the DTCCSK codeset. For example, if $SF = 200$ and $L_T = 10$, the minimum values of L and M are 11 and 2048, respectively. In this case, M_P is 48. Compared with the case that uses only the vertical truncation, flexibility and efficiency of the system configuration are both increased by using the horizontal truncation and the vertical truncation together.

In Table 1, given the condition that $SF = 100$, we show the minimum sizes of the DTCCSK

Table 1. Example of DTCCSK codeset sizes ($SF = 100$)

L_T	3	4	5	6	7	8	9	10	11	12
M_T	300	400	500	600	700	800	900	1000	1100	1200
L	9	9	9	10	10	10	10	10	11	11
M	512	512	512	1024	1024	1024	1024	1024	2048	2048
M_P	212	112	12	424	324	224	124	24	948	2096

codeset under the various values of L_T by using (6). We can see that L increases as L_T increases. To minimize the zero padding under the same value of L, it is better to choose L_T corresponding to the minimum M_P. For example, M_P under the condition that $L_T = 5$ is smaller than that under the condition where $L_T = 3$.

Ⅳ. Performance Evaluation

To verify the performance of DTCCSK, we developed a simulator for SSA under asynchronous systems. The simulator essentially follows the system model described in Section Ⅱ. In the simulator, the generation of traffic packets follows an independent Poisson process. A modulated signal undergoes lognormal shadow fading that represents the joint effect of return mobile link satellite shadowing, fading, and the packet transmission control algorithms. The lognormal r.v. is assumed to be decorrelated among all the return link packets and to be constant over the packet duration. Then, additive white Gaussian noise is added to the signals. For signature sequences, we assume that there are sufficient signature sequences in the system to make the code collision probability negligible. If more than 16 signature sequences are used, the probability of code collision is less than 10^{-4}[1]. In addition, the code ID proposed by C. Schlegel[10] can be used to guarantee a sufficient number of signature sequences.

In this paper, we omit the encoding and decoding processes for forward error correction, so that we can only observe the performance of the spreading technique. Because satellite communication guarantees line-of-sight, we set E_B/N_0 as 13.7 dB. The number of bits in a packet is 100. If L_T is not an aliquot part of 100, the minimum numbers of zero bits are padded to make the packet divisible by L_T. The mean value of the lognormal shadowing process is -3 dB, and its variance is 2 dB. These values represent the case of sufficient fading at the gateway[5].

To verify the performance enhancement, we measure the PLR according to the number of interfering packets K and channel throughput T according to channel traffic load G. The units of T and G are the same as the number of packets per packet duration. We also obtain the spectral efficiency according to the normalized traffic load, G_{Norm}, where $G_{Norm} = G/SF$. We use MATLAB as a simulation tool and simulate 1 million packets per each simulation result.

Fig. 3 shows the PLRs when SF is 100. We derived these results by colliding K number of packets with one arbitrary packet with random delay. These results show how many packets can be transmitted simultaneously without a packet loss. To verify the effect of the symbol length, i.e., the size of DTCCSK codeset, we show the results under various values of L_T in Table 1. First, we can observe that the performance increases as L_T increases. Even if L_T is small (such as 3), it can be seen that the performance of DTCCSK/SSA is superior to that of DS/SSA. In other words, with the same transmit power, a DTCCSK/SSA system can tolerate a greater number of collisions than a DS/SSA system. Considering that the values of SF are the same between DS/SSA and DTCCSK/SSA, these results show that DTCCSK is more suitable for M2M applications than DS.

Fig. 4 shows the channel throughput according to G under various values of SF and L_T. It can be

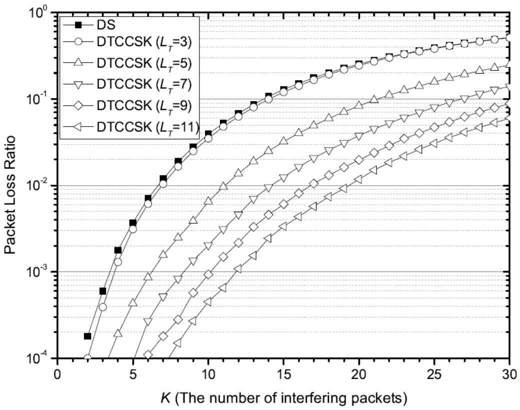


Fig. 3. Comparison of PLR ($SF = 100$)

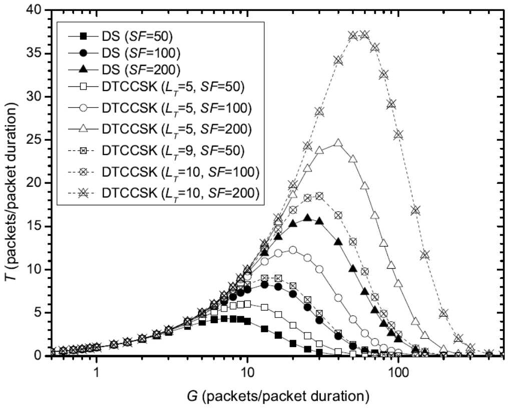


Fig. 4. Comparison of throughput ($SF=20, 50, 100$)

seen that more packets can be transmitted simultaneously as SF increases. A noteworthy result is that when L_T is sufficiently large, DTCCSK/SSA with low SF even outperforms DS/SSA with high SF.

Fig. 5 shows the spectral efficiency under similar values of SF. For MOS/SSA, we set $L=10$ and $M=1024$. As we already mentioned, the spectral efficiency of MOS/SSA is much higher than that of DS/SSA. The spectral efficiency of DTCCSK/SSA has a dynamic range according to L_T, and approaches that of MOS/SSA as L_T increases. Considering the implementation complexity, this result shows that DTCCSK/SSA is more efficient than MOS/SSA from a practical point of view.

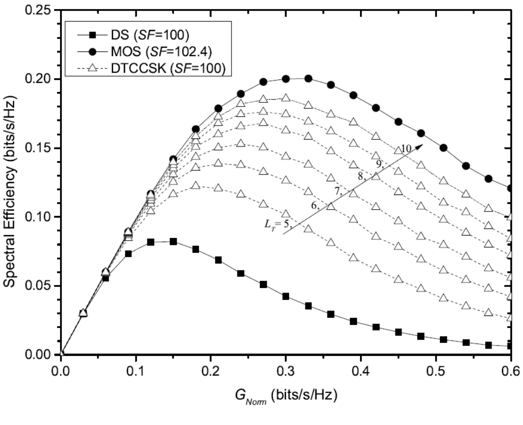


Fig. 5. Comparison of spectral efficiency

Ⅴ. Conclusion

To increase the number of simultaneous transmissions of M2M traffic in SATNETs, we proposed a new spreading technique, called DTCCSK, for SSA. Because the design of DTCCSK is based on CCSK, the implementation complexity is much simpler than that of MOS. The vertical truncation of DTCCSK is used to support various values of SF and to increase data rates. In addition, the horizontal truncation of DTCCSK reduces the required code length and allows for an efficient system design. We also described an approach for appropriately selecting the symbol length from a given SF. We verified the performance of DTCCSK/SSA through extensive simulations. The results show that, from a practical point of view, DTCCSK/SSA is more suitable than DS/SSA and MOS/SSA.

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노 홍 준 (Hong-jun Noh)

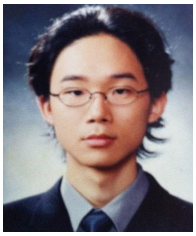
2008년 2월 : 아주대학교 정보 및 컴퓨터공학과 졸업

2015년 2월 : 아주대학교 컴퓨터공학과 박사

2015년 3월~현재 : LIG넥스원

<관심분야> 위성통신, 지상/위성 통합 네트워킹, 이동통신

박 형 원 (Hyung-won Park)



2003년 2월 : 아주대학교 정보 및 컴퓨터공학과 졸업

2005년 2월 : 아주대학교 정보통신공학과 석사

2009년 8월 : 아주대학교 정보통신공학과 박사

2009년 9월~현재 : LIG넥스원

<관심분야> 전술데이터링크, 군 위성통신, 이동통신

임 재 성 (Jae-sung Lim)

1983년 2월 : 아주대학교 전자공학과 학사

1985년 2월 : KAIST 영상통신 석사

1994년 8월 : KAIST 디지털통신 박사

1998년 3월~현재 : 아주대학교 소프트웨어융합학과 정교수

<관심분야> 이동통신, 무선네트워크, 국방전술통신