Analysis of Three-Phase Multiple Access with Continual Contention Resolution (TPMA-CCR) for Wireless Multi-Hop Ad Hoc Networks

Yeongyoon Choi and Aria Nosratinia

Abstract: **In this paper, a new medium access control (MAC) protocol entitled three-phase multiple access with continual contention resolution (TPMA-CCR) is proposed for wireless multi-hop ad hoc networks. This work is motivated by the previously known three-phase multiple access (TPMA) scheme of Hou and Tsai [2] which is the suitable MAC protocol for clustering multi-hop ad hoc networks owing to its beneficial attributes such as easy collision detectible, anonymous acknowledgment (ACK), and simple signaling format for the broadcast-natured networks. The new TPMA-CCR is designed to let all contending nodes participate in contentions for a medium access more aggressively than the original TPMA and with continual resolving procedures as well. Through the systematical performance analysis of the suggested protocol, it is also shown that the maximum throughput of the new protocol is not only superior to the original TPMA, but also improves on the conventional slotted carrier sense multiple access (CSMA) under certain circumstances. Thus, in terms of performance, TPMA-CCR can provide an attractive alternative to other contention-based MAC protocols for multi-hop ad hoc networks.**

Index Terms: **Anonymous acknowledge (ACK), clustering protocol, contention resolution, medium access control (MAC) protocol, three-phase multiple access (TPMA), wireless multi-hop ad hoc networks.**

I. INTRODUCTION

In the variety of current wireless communication systems, ad hoc network has been settled to gain more popularity for supporting various wireless communication services. As mobile devices become smaller in size and so shrink their radio coverage for longer battery life, this ad hoc type of network is gradually evolved for covering up to the area where is beyond a single-hop away from the access point of infra-structured networks. In such ad hoc circumstances, the mobile nodes usually do not have direct links to all the others including the base stations geographically dispersed in the service area. Hence it may be commonly required to relay data packets over many other nodes before those packets are reached to the destination, resulting in multi-hop ad hoc networks [5].

Manuscript received July 09, 2009; approved for publication by K. C. Chen, Guest Editor, November 03, 2010.

This work was supported by a research grant (UD100021ID) of the Agency for Defense Development (ADD), Korea.

Y. Choi is with Department of Electrical Engineering, Korea Military Academy, P.O. Box #77, Gong-neung, Nowon, Seoul, Republic of Korea, email: ychoi@kma.ac.kr.

A. Nosratinia is with Department of Electrical Engineering, University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080, U.S.A., email: aria@utdallas.edu.

Since a large-scaled ad hoc network connects all the mobile nodes in a multi-hop fashion, developing the appropriate management protocols of such network including medium access control (MAC) and routing schemes has been a great challenge to network designers. In order to alleviate the perturbation of such multi-hop ad hoc networks, organizing multi-clusters for large-scaled ad hoc network has been admitted as one of the most prospective solutions due to the three main advantages of clustering, such as the spatial reuse of resources, the easier update of hierarchical topology and the reduced information exchanges for routing [1]. And also, the MAC protocols, which are responsible for coordinating the access from active nodes in the network, are of significant importance since the wireless ad hoc networks are inherently prone to errors [3].

In [2], the more efficiently deployed clustering protocol, called access-based clustering protocol (ABCP), than any other previous clustering was introduced. ABCP had shown one big difference from the previous clustering protocols in that the clustering formation is mainly based on the newly proposed MAC protocol which is different from the conventional IEEE 802.11-based MAC protocol. Hou and Tsai [2] called their MAC protocol for forming clusters as three-phase multiple access (TPMA) scheme from the fact that the medium access control is performed in three relatively simple phases. And they showed the whole performance of ABCP can be improved by this efficient MAC protocol for the control channel that supports faster contention resolutions and brings to high throughput.

In this paper, the new three-phase multiple access with continual contention resolution (TMPA-CCR) protocol is proposed as a new MAC layer protocol for wireless multi-hop ad hoc networks. The proposed method builds on the ideas of a MAC protocol known as TPMA [2], which was designed for the purposes of clustering in wireless multi-hop ad hoc networks. The original TPMA has several advantages that are attractive for multi-hop ad hoc networks, including a simple signalling structure as well as anonymous acknowledgment (ACK), but does not enjoy very good throughput performance. We modify this TPMA-based MAC scheme by letting all the contending nodes continuously participate in contentions until a winner node for an access arises. The more detailed descriptions of TPMA-CCR protocol are presented in section II with some backgrounds and related works on TPMA.

Through the mathematical performance analysis, the normalized throughput of the suggested protocol is carefully derived and compared to not only that of the original TPMA, but also those of more conventional MAC schemes in wireless networks such as additive links on-line hawaii area (ALOHA) and slot-

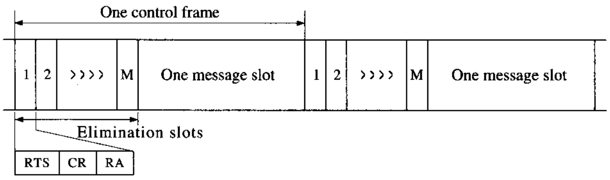


Fig. 1. The original TPMA based MAC frame format.

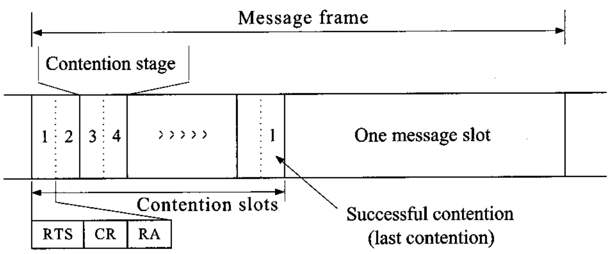


Fig. 2. The frame format of the new TPMA-CCR.

ted carrier sense multiple access (CSMA). The derivations use the reciprocal of the average contention resolution time, i.e., the successful packet interdeparture time as derived in [7], [8]. The results show that the evolution of this TPMA-based protocol will provide the improved throughput performance.

II. TPMA AND TPMA-CCR

A. Background and Related Work

The TPMA idea was originally suggested for the control channel of clustering ad hoc networks [2]. In the original TPMA, a dedicated control channel is used for disseminating control messages. As shown in Fig. 1, the control channel is partitioned into fixed-size frames (also known as control frames) composed of M mini-slots followed by a designated message slot. The number of mini-slots is fixed for all control frames, and the sum of all mini-slots is called as an elimination slot.

Each mini-slot is further divided into three phases, giving rise to the name of the protocol, *Three-Phase Multiple Access*. The three phases are: Request to send (RTS) where nodes make their request for transmission, collision report (CR) where nodes report collisions that just occurred in the RTS, and receiver available (RA). In the RA phase, if nodes only receive one RTS indication in phase 1, they send a RA indication to acknowledge this RTS request.

A contender node transmits an RTS signal during the first phase and tries to sense the presence of collisions. In the absence of collision, i.e., no neighbour contender, it checks the presence of RA signal from a possible receiver node (third phase). If it senses a RA, the node has won the contention, so it will wait throughout the remaining mini-slots and transmits control data message in the designated control message slot.

If there is an active node within 2 hops of this node, the CR signal will be detected in phase two, and a contention resolution process will be initiated. At this point, the node knows that at least one of its neighbours has experienced a collision. The node will then act as follows: with probability p, the node makes another attempt by sending another RTS in the next mini-slot. With probability $1-p$, the node backs off from the contention, abandons the entire message slot, and waits for the next frame. Thus, once a collision has been indicated, the node will be eliminated from the contention with probability $1-p$. This process continues until a winner arises and claims the channel.

To summarize, the CR phase detects the collision caused by neighbouring contenders in the same broadcasting zone, while the RA phase detects the existence of possible receiver nodes in the same zone. The RA addresses the issue of *receiving erasure* which is named in [2] because of the half-duplex restriction, i.e., a node cannot transmit and receive on the same channel simultaneously. For instance, if a node sends an RTS but does not detect any CR and RA indication in the following two phases, this node is either isolated or all its one-hop neighbours send RTSs too. For this reason, all the three phases RTS, CR, and RA are essential.

In the interest of efficiency, the signalling of RTS, CR, and RA should be simple and compact. In each phase, a simple notification of absence/presence/collision (0/1/c) is enough [2]. The signal should be only long enough that a receiver can discriminate between the three states.

A scheme such as TPMA can in principle be competitive with the conventional exponential backoff in IEEE 802.11, because it has attributes that are beneficial to broadcast-type networks, including collision detectible, anonymous ACK, and simple signaling format [2]. However, because nodes are rapidly removed from contention to avoid consecutive collisions, there is a nontrivial probability that all contenders may abandon the message slot before the end of the elimination, so the designated message slot may be wasted. The designated message slot can also be wasted when two or more nodes are still in contention until the final mini-slot, i.e., when no winner arises because of the limited (fixed) number of elimination slots per control frame. The lack of a clear winner, either through rapid back-off or because of a lack of resolution, clearly degrades network performance.

B. The TPMA-CCR Protocol

As mentioned earlier, the basic idea of TPMA includes several features that are very attractive for wireless sensor networks. However, the removal of colliding nodes from the contention before a winner has been determined can lead to some weaknesses in performance. In the new protocol (TPMA-continual contention resolution (CCR)), the contending nodes will remain for the continued contention until a clear winner of the channel has been determined. The issue of excessive collisions is addressed by allowing only a fraction p of the contending nodes to compete for the channel at each point in time, via random self-selection. In this way, a varying mixture of nodes is allowed into the contention pool such that performance is improved. The details of the TPMA-CCR protocol are as follows.

We first start by specifying a modified MAC frame format as in Fig. 2. The TPMA-CCR protocol keeps the three-phase structure of the original TPMA mini-slots, i.e., each contention mini-slot has three phases known as RTS, CR, and RA. However, the overall structure of each message frame is altered compared with TPMA. To begin with, the mini-slots are not identical; the function and operation of the odd and even mini-slots will be slightly different, as explained in the sequel. Each set of two consecutive mini-slots is grouped together into *one contention stage*. Also, the total number of mini-slots is no longer fixed; instead, the

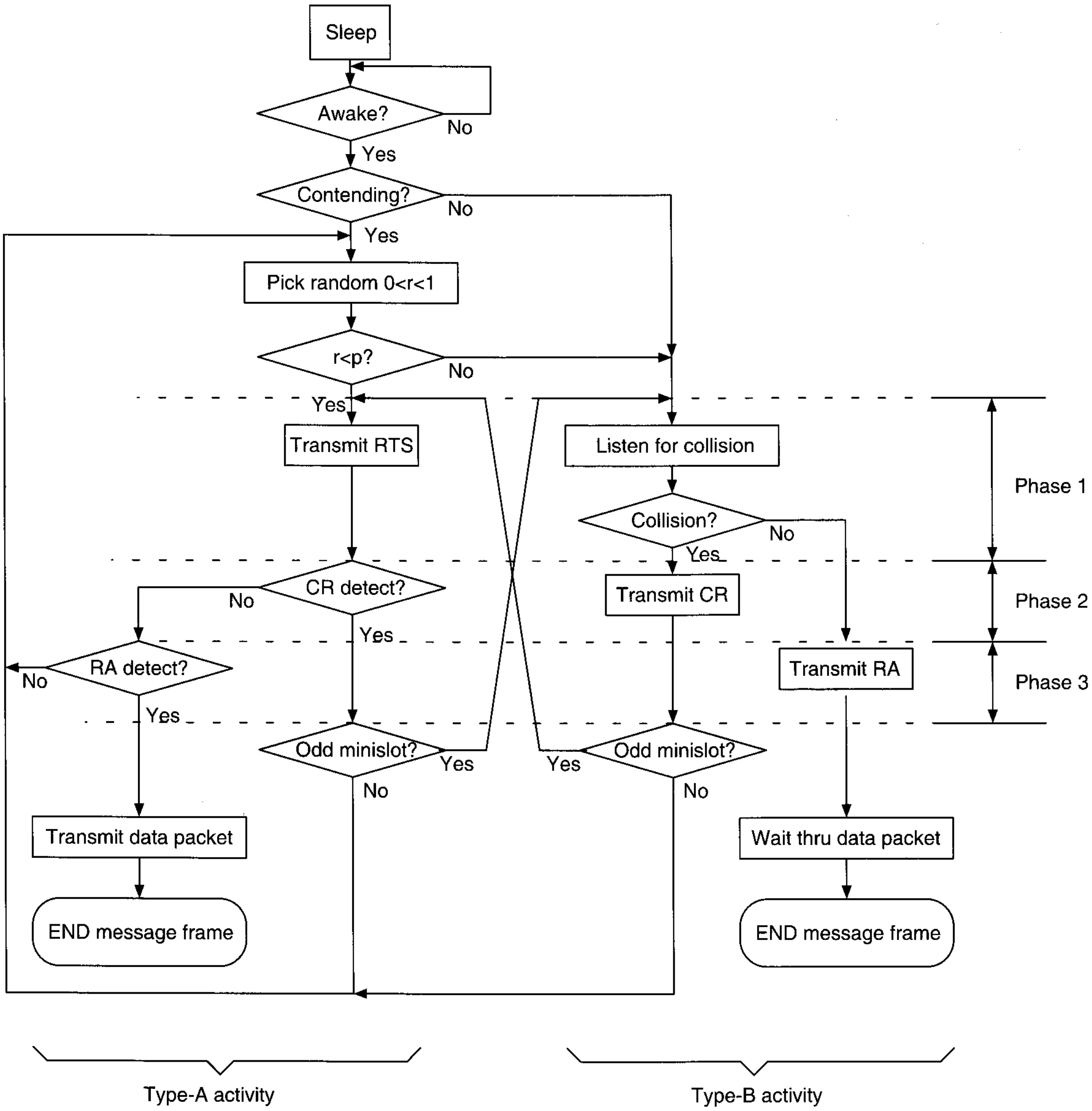


Fig. 3. The flow diagram of contention resolution procedures at every contention stages.

contention process is continued until a clear winner arises. This gives rise to a variable-length message frame, which can be supported by well-known synchronization mechanisms in wireless communication.

Subject to this frame format, the operation of the protocol is as follows. At the beginning of the message frame, each node that desires to use the channel will put itself either in a contending group (which we shall call type-A) with probability p, or in a listening group (which we shall call type-B) with probability $1-p$. If a node is type-A, it will be active in the first mini-slot and will transmit an RTS. All type-B nodes, as well as nodes that do not wish to contend in the same broadcasting zone, will listen for collisions.

If any type-B node detects a collision, it will transmit a CR signal that will be received by type-A nodes, telling them that there was no clear winner in this mini-slot. It is assumed that multiple CR signals are not detrimental to each other. If there exists at least one listening node (either type-B or otherwise) that does not detect a collision, it will send a RA signal. Upon receiving the RA signal, the contending transmitter will know that it has won the channel, and commences transmission.

In the event that no winner arises in the first mini-slot, each type-A node will revert to type-B and vice versa, the three-phase operation will be repeated for the second mini-slot.

Finally, if at the end of the second mini-slot no clear winner of the channel arises, the all contending nodes are repeating the operation of contention which starts from the beginning. The nodes will make a random choice (independent of their previous choice) of being type-A or type-B, and go through the process of three-phase contention resolution. This overall process continues until a clear winner arises in the channel.

The flow diagram of this protocol is shown in Fig. 3. Note the vertical distinction of the three phases of the TPMA-CCR protocol and the horizontal separation between the type-A and type-B activities.

There are also *receiving erasure* problem as in [2], for example, if a CR is not received (no collision has been detected) but no RA is received either, this can be a sign that there was no type-B node available to listen and/or check for collisions. In the new TPMA-CCR protocol, the problem is easily overcome by having all contenders (type-A) continue the contention at the following mini-slots by repeating random self-selection as type-A or type-B node until a winner arises as shown in Fig. 3. The repeated random self-selections provide the possible type-A and type-B nodes at the continuing contention stages.

We note that the TPMA-CCR can be considered the evolution of another algorithm known as TPMA alternating contention resolution (TPMA-ACR) [9] developed by a subset of the present authors.

III. THROUGHPUT ANALYSIS OF TPMA-CCR

In this section, the careful derivation of the performance analysis of this new protocol is derived and the comparisons between the new protocol and rather conventional ones such as ALOHA and CSMA protocols are done with the average contention resolution time and throughput as well.

A. Fundamentals for Analysis

The throughput of the system, in this paper, is defined as the average number of successful packet transmissions completed during a given interval$[0, t]$, essentially the normalized length of message data packet, which is a classical definition [8].

Let $\{X^{(n)}; n = 1, 2, \cdots\}$ be a sequence of packet inter departure times. The starting time is set at the end of the successful transmission of an arbitrary packet. Each interval $X^{(n)}$ begins at the end of the previously successful transmitted packet, and ends at the *end* of the transmission of the next successful packet. It is easy to show that for memoryless MAC protocols, the inter-departure times are independent, identically distributed (i.i.d.) random variables. The time of the completion of the n_{th} successful transmission is:

$$S^{(n)} = X^{(1)} + X^{(2)} + \cdots + X^{(n)} \quad n = 1, 2, \cdots \tag{1}$$

Therefore, $\{S^{(n)}; n = 1, 2, \cdots\}$ is a *renewal process* [10]. For time $t > 0$, let $D(t)$ be the number of successful transmissions completed during an interval $[0, t]$, i.e.,

$$D(t) = \max\{n;\ S^{(n)} \leq t\} \tag{2}$$

Due to the *elementary renewal theorem*

$$\lim_{t \to \infty} \frac{\overline{D(t)}}{t} = \frac{1}{\overline{X}} \tag{3}$$

where $\overline{X}$ is the mean of the packet inter-departure times from the system. Thus, (3) represents the *throughput, S* of the system according to our definition of the throughput, which is the reciprocal of the average packet inter-departure times.

B. Throughput of TPMA-CCR

Following [8] , the successful packet interdeparture time X is composed of the *contention period* and the *successful transmission period.* The contention period in turn is divided into *idle* and *unsuccessful transmission periods* (identically distributed) as shown in Fig. 4(a).

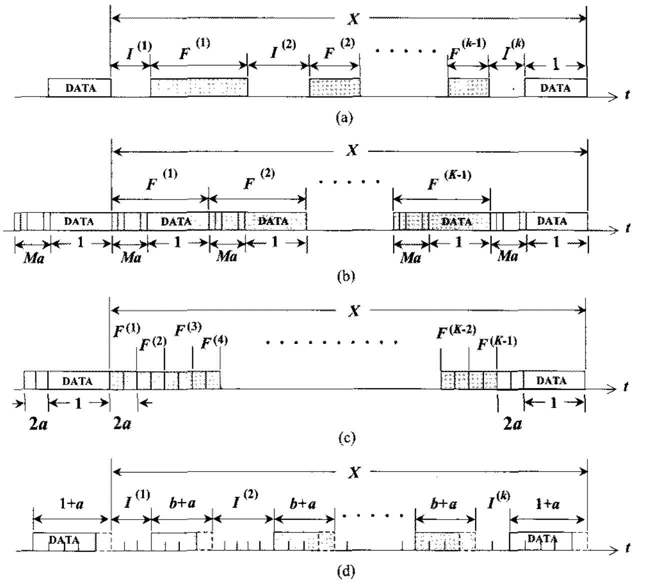


Fig. 4. Packet interdeparture times X: (a) Generic protocol, (b) TPMA, (c) TPMA-CCR, and (d) slotted CSMA.

Now, let K be the number of transmission periods (successful or unsuccessful) included in X. Clearly the last transmission is the only successful one. Let $I^{(k)}$ and $F^{(k)}$ be the duration of the k_{th} idle period and unsuccessful period respectively, and T be the duration of the successful transmission period. Then,

$$X = \sum_{k=1}^{K-1} [I^{(k)} + F^{(k)}] + I^{(K)} + T \tag{4}$$

where $I^{(k)}$ and $F^{(k)}$ are i.i.d. Thus, the sequence of renewal cycle durations $\{I^{(k)} + F^{(k)}, k = 1, 2, \cdots\}$ are independent and identically distributed, and furthermore $I^{(K)} + T$is independent of the previous cycles. Hence, the mean of X is:

$$\overline{X} = (\overline{K} - 1)(\overline{I} + \overline{F}) + \overline{I} + \overline{T} \tag{5}$$

where it is assumed that $F^{(k)}$ and T are independent of $I^{(k)}$.

Let ω be the probability of successful transmission, then it is clear the K has a geometric distribution [8], i.e.,

$$\begin{aligned} Pr[K = k] &= (1 - \omega)^{k-1} \cdot \omega \quad k = 1, 2, \cdots, \\ \overline{K} &= 1/\omega. \end{aligned} \tag{6}$$

Therefore, given a specific MAC protocol, $\overline{X}$ can be easily computed by (5) and (6) if ω and the mean of $I, F,$ and T are known. These mean values depend on the particulars of the MAC protocol.

B.1 The Original TPMA [2]

As shown in Fig. 4(b), in TPMA no idle period exists between unsuccessful transmissions. Furthermore, the length of both successful and unsuccessful transmissions during contention is fixed via the format of the MAC protocol which has exactly M elimination mini-slots followed by one message data slot. For easier exposition, the size of mini-slot a is normalized by the data slot.

Hence, the successful packet interdeparture time of the original TPMA based MAC protocol is

$$X = \sum_{k=1}^{K-1} F^{(k)} + T \tag{7}$$

where $F^{(k)}$ and T are fixed deterministic variables with $F^{(k)} = Ma + 1$ and $T = Ma + 1$ respectively. So, the mean of X, i.e., the average contention resolution time of the protocol is

$$\overline{X} = (Ma + 1)/\omega \tag{8}$$

with the probability of the successful transmission

$$\omega = \sum_{k=1}^{M} np^{k-1}(1-p)^{n-1}\left[\left(\sum_{i=0}^{k-2} p^i\right)^{n-1} - \left(\sum_{i=0}^{k-3} p^i\right)^{n-1}\right] \tag{9}$$

where n is the total number of contenders in the same broadcasting zone. The results up to this point follow [2].

B.2 The TPMA-CCR Protocol

In this new protocol, the contention period consists (possibly) of a series of unsuccessful transmission periods whose sizes are fixed with two alternative contention mini-slots as shown in Fig. 4(c). Similarly to the previous case, there are no idle periods between unsuccessful or successful transmission periods.

Hence, the successful packet interdeparture time of the new TPMA-CCR MAC protocol is same as in (7). For the new protocol, however, $F^{(k)}$ takes fixed deterministic values $F^{(k)} = 2a$ and T is random variable due to the randomness of having winner at the first mini-slot or pair-wise mini-slot of the last contention stage. Consequently, the mean of X for the new protocol is

$$\overline{X} = 2a \cdot (\overline{K} - 1) + \overline{T} \tag{10}$$

where $\overline{T} = 1 + \frac{3a}{2}$, which can be trivially shown since the possibilities for a winner to arise at each mini-slots of the last contention stage are equal to $1/2$.

The probability of successful transmission $\omega = 1/\overline{K}$ for this protocol can be derived by considering the probability of the event that a winner arises at a given contention stage. A moment's reflection will show that a successful transmission is possible under two scenarios: if exactly one of the contending nodes is classified as type-A, and all others are type-B, or alternatively if exactly one node is type-B, and all others are type-A. At each mini-slot, denote the number of type-A nodes with random variable N_A and the number of type-B nodes with random variable N_B. It follows:

$$\begin{aligned} &Pr\,\{\text{a winner arises at the contention stage}\} \\ &= Pr\,\{N_A{=}\,1\} + Pr\,\{N_B{=}1\} - Pr\,\{N_A{=}1, \& N_B{=}1\} \\ &= {}_nC_1 p(1-p)^{n-1} + {}_nC_1(1-p)p^{n-1} = \omega, \end{aligned} \tag{11}$$

since $\Pr\{N_A = 1 \;\&\; N_B = 1\} = 0$ for $n > 2$.

From (10) and (11), the average packet interdeparture times for this new new TPMA-CCR protocol is

$$\overline{X} = \frac{2a/n}{p(1-p)^{n-1} + (1-p)p^{n-1}} - \frac{a}{2} + 1 \tag{12}$$

where $n > 2$ is the total number of contenders. Therefore, the throughput of the new protocol can be followed as the reciprocal of (12).

B.3 The Slotted CSMA Protocol

For the purpose of comparison, we also derive the throughput analysis of Slotted CSMA protocol where the slot size is equal to a, the ratio of the signal propagation delay to the packet length. Most procedures for an analysis in this section follow the steps shown in [8].

The packet interdeparture time X for Slotted CSMA can be depicted in Fig. 4(d). Fig. 4(d) shows the unsuccessful transmission period for CSMA without collision detection (CD) lasts $b + a$, where b is the unsuccessful packet length and $a \leq b = 1$. Thus, the average packet interdeparture time for Slotted CSMA can be represented as

$$\begin{aligned} \overline{X} &= (\overline{K} - 1)(\overline{I} + 1 + a) + \overline{I} + 1 + a \\ &= \overline{K}(\overline{I} + 1 + a) \end{aligned} \tag{13}$$

since the transmission periods are of constant length as

$$T = F = 1 + a. \tag{14}$$

In this protocol, it is obvious that a transmission is successful when only one user starts to transmit with the fact that none of the other users have started transmission at the same time. Thus, we have the probability of successful transmission for this protocol as follows[8]:

$$\omega = U/1 - E \tag{15}$$

where

$$E = \prod_{i=1}^{n}(1 - p_i), \quad U = \sum_{i=1}^{n} p_i \prod_{\substack{j=1 \\ (j \neq i)}}^{n} (1 - p_j) \tag{16}$$

with the assumption that user i starts to transmit(after sensing any idle slot) with probability p_i independently of all others.

And the channel idle period I of this protocol has also a geometric distribution as

$$Pr[I = ma] = E^m \cdot (1 - E), \quad m = 0, 1, 2, \cdots \tag{17}$$

which leads the average idle period

$$\overline{I} = \frac{E}{1 - E} a. \tag{18}$$

Hence, the average packet inter-departure times for Slotted CSMA protocol can be simply derived from (6), (13), and (18) as follows:

$$\overline{X} = \frac{1 + a - E}{U}. \tag{19}$$

B.4 Numerical Results and Remarks

The throughput for the original TPMA protocol depends critically on the appropriate choice of the number of elimination slots M and the probability of remaining in contention p, as shown in (8) and (9). The new TPMA-CCR MAC protocol is more balanced in that throughput is the function of probability

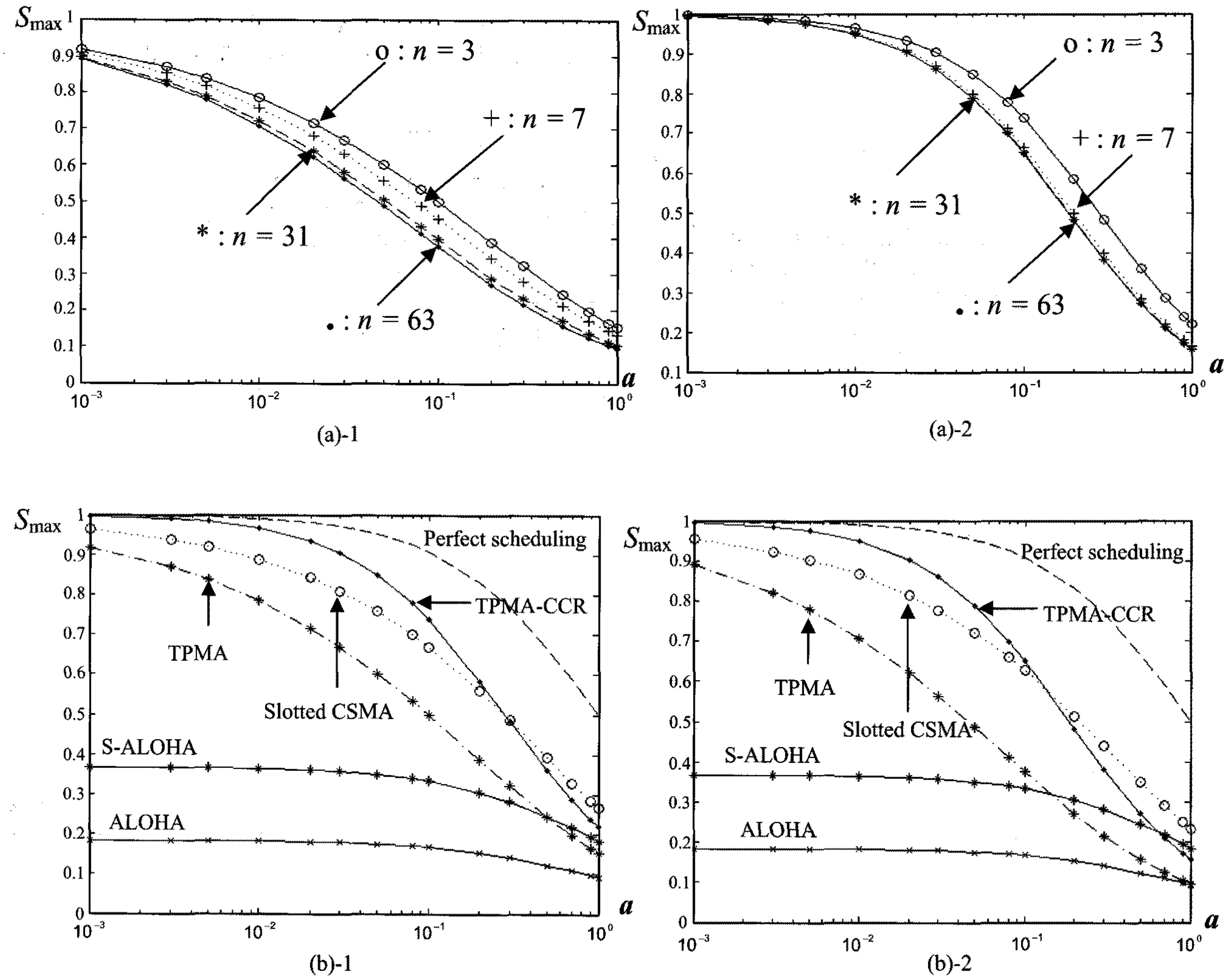


Fig. 5. The maximum throughput curves for various MAC protocols: (a)-1 Origianl TPMA MAC, (a)-2 new TPMA-CCR MAC, (b)-1 $n = 3$, and (b)-2 $n = 63$.

to be contended at the one of alternative slots. Fig. 5(a) shows throughput values that are optimized with respect to the parameters (e.g., M and p). The optimal throughput is depicted for varying number of contenders. Fig. 5(b) shows the maximum throughput curves for the various MAC protocols including conventional ones studied in [8]. To perform a fair comparison, the throughputs for ALOHA systems and perfect scheduling are scaled by $1 + a$ since practical ALOHA systems are assumed to be in an environment of nonzero propagation delay($a > 0$) [8]. And also, the case of all identical users($p_i = p$, for all i) are considered for Slotted CSMA protocol to obtain the maximum allowable throughput.

IV. CONCLUSION

We have proposed a new MAC scheme entitled Three-Phase Multiple-Access with Continual Contention Resolution (TPMA-CCR) which is suitable for wireless sensor networks due to its beneficial features such as the simple format and procedures of signaling and collision delectability with anonymous ACK, which are suitable for broadcast-type wireless multi-hop networks. The performance of the TPMA-CCR protocol was analyzed, and it was shown that the maximum throughput of the new protocol is superior to the original TPMA, and furthermore it is also better than conventional slotted CSMA under certain circumstances, e.g., relatively small-sized mini-slots. The attractive throughput performance of TPMA-CCR implies that it is quite competitive compared with other MAC protocols that are designed only with energy-efficiency in mind, which has sometimes led to sacrificing their classical performance parameters such as throughput [4].

Future work involves improvements to obtain better throughput for larger-sized mini-slots.

REFERENCES

[1] C. R. Lin and M. Gerla, "Adaptive clustering for mobile wireless networks," *IEEE J. Sel. Areas. Commun.*, vol. 15, pp. 1265–1275, 1997.

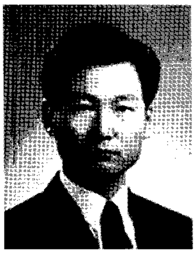
[2] T. C. Hou and T. J. Tsai, "An access-based clustering protocol for multihop wireless ad hoc networks," *IEEE J. Sel. Areas. Commun.*, vol. 19, num. 7, pp. 1201–1210, July 2001.

[3] S. Kumar, V. S. Raghavan, and J. Deng, "Medium access control protocols for ad hoc wireless networks: A survey," *Ad Hoc Netw.*, vol. 4, num. 3, pp. 326–358, 2006.

[4] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multi-hop wireless ad hoc networks?," *IEEE Commun. Mag.*, pp. 130–137, June 2001.

[5] H. Wu and Y. Pan, *Medium access control in wireless networks, volume II: Practice and standards, Nova Science Publishers*, 2007.

[6] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," *Wireless Netw.*, vol. 11, no. 1, pp. 55–66, 2005.
[7] J. Deng and Y. S. Han and Z. J. Haas, "Analyzing split channel medium access control schemes with ALOHA reservation," in *Proc. ADHOC-NOW*, 2003, pp. 128–139.
[8] H. Takagi and L. Kleinrock, "Output processes in contention packet broadcasting systems," *IEEE Trans. Commun.*, vol. 33, no. 11, pp. 1191–1199, Nov. 1985.
[9] Y. Choi and Y. Kim, "A new three phase multiple access based MAC protocol for clustering wireless multi-hop ad hoc networks," in *Proc. COMSNETS*, 2007, pp. 7–12.
[10] S. Karlin and H. W. Taylor, *A first courses in stochastic processes, New York Academic*, 1975.



Yeongyoon Choi was born in Kwang-Ju, Korea, on September 1959. He received the B.S. degree from the Korea Military Academy, Seoul, Korea in 1982, and the M.S. and Ph.D. degrees from the University of Southern California, Los Angeles, in 1986 and 1989, respectively, all in electrical engineering. In January 1990, he joined the Faculty at the Department of Electrical Engineering, Korea Military Academy, where he is currently a Professor. He was a Visiting Research Fellow at the department of communications, FOI(Swedish Defense Research Agency), Linkoping, Sweden, from 2001 to 2002 and also a Visiting Professors of Electrical Engineering at the University of Texas at Dallas from 2008 to 2009. His research interests include broadband wireless multimedia communication system , capacity analysis and resource management of multimedia DS-CDMA cellular system, frequency diversity techniques in OFDM system, and cross-layered design issues on MAC and Clustering protocols for wireless *ad hoc* networks.

Aria Nosratinia is Jonsson Distinguished Professor of Electrical Engineering at the University of Texas at Dallas. He received his Ph.D. in Electrical and Computer Engineering from the University of Illinois at Urbana-Champaign in 1996. He has held visiting positions in Princeton University, Rice University, and UCLA. He is an Officer and Member of Board of Governors of the IEEE Information Theory society, as well as associate editor for the IEEE Transactions on Information Theory and IEEE Transactions on Wireless Communications. In the past he has served on the editorial board of IEEE Wireless Communications Magazine, IEEE Transactions on Image Processing, IEEE Signal Processing Letters, and Journal of Circuits, Systems and Computers. He has served on the technical committees of many conferences including the technical program committee of Globecom for the past 7 years, as well as on the organizing committee of the International Symposium on Information Theory in 2010. Dr. Nosratinia is a Recipient of the National Science Foundation Career Award. He was elevated to the Grade of IEEE Fellow "for contributions to multimedia and wireless communications."