무선 애드혹 네트워크에서 수신자 중심 캐리어 센싱 기법

(A Receiver-Centric Carrier Sense Technique for Wireless Ad Hoc Networks)

유 준[†] 김 종 권[††]
(Joon Yoo) (Chong-kwon Kim)

요 약 대부분의 애드혹 네트워크에서는 데이터 송신자가 채널 검사를 통해 전송 방법을 결정하는 송신자 중심의 캐리어 센싱 (carrier sensing)을 사용한다. 그러나 데이터 송신자 중심의 캐리어 센싱은 물리적 (physical) 캐리어 센싱과 가상 (virtual) 캐리어 센싱을 사용함에도 불구하고 노출 터미널 문제 (exposed terminal problem)와 숨겨진 터미널 문제 (hidden terminal problem)를 모두 야기시킨다. 본 논문에서는 데이터 수신자가 지역적 채널 검사를 통해 패킷 전송을 시도하는 새로운 수신자 중심 캐리어 센싱 기법을 제안한다. 수학적 분석과 시뮬레이션 평가를 통해 본 논문에서 제안한 수신자 중심 캐리어 센싱 기법이 기존에 제안된 수신자 중심 센싱 기법에 비해 20.9% 이상의 성능 향상을 보인다.

키워드 : 캐리어 센스, IEEE 802.11 무선랜, 무선 애드혹 네트워크, 수신자-중심

Abstract Most wireless ad hoc networks use sender-centric carrier sensing where a data sender determines the transmission timing through channel assessment. However, sender-centric carrier sensing suffers from both exposed and hidden terminal problems even with physical and virtual carrier sensing. In this paper, we propose a new receiver-centric carrier sense (RCS) technique where a data receiver triggers packet transmission based on local channel assessment. Through both numerical analysis and simulation studies, we show that the proposed RCS achieves up to 20.9% higher throughput than previous receiver-centric approaches.

Key words : Carrier sense, IEEE 802.11 WLAN, wireless ad hoc networks, receiver-centric

1. Introduction

Recently advanced wireless technology has led to the development of self-organized and distributed wireless ad hoc networks. The IEEE 802.11 medium access control (MAC) protocol [1], widely employed to access the shared wireless medium, uses physical carrier sensing (PCS) and virtual carrier sensing (VCS) mechanisms to avoid interference. However, it is still susceptible to the exposed and hidden terminal problems [2] and many *sender-centric* carrier sense solutions [3,4] have been proposed to overcome this problem. However, the fundamental limit of sender-centric carrier sense protocols is that senders can only heuristically infer the channel status of the receiver so that various problems still persist [5]. Some *receiver-centric* solutions [6-8] have been previously studied. Although these schemes improve from the sender-centric approaches, they still suffer from the hidden [6] or exposed terminal problems [7,8].

· 본 논문은 정부(교육과학기술부)의 재원으로 한국연구재단(NRF-2009-352- D00261) 및 (R01-2007-000-20154-0), 지식경제부 및 정보통신연구 진흥원의 대학 IT연구센터 지원사업(IITA-2008-C1090-0803-0004)의 지원을 받아 수행된 연구임

† 비 회 원 : UCLA Computer Science Dept Postdoc
joonyoo2@ucla.edu
†† 종신회원 : 서울대학교 컴퓨터공학과 교수
ckim@popeye.snu.ac.kr

논문접수 : 2009년 10월 19일
심사완료 : 2010년 3월 3일

정보과학회논문지: 정보통신 제37권 제4호(2010.8)

In this paper, we present a new *receiver-centric carrier sense* (RCS) protocol for wireless ad hoc networks. In RCS, the data receiver initiates the *transmission by conducting smart and accurate* channel assessment so that the hidden terminal problem is solved, while the exposed terminal problem is solved by the data sender neglecting physical carrier sensing and using virtual carrier sensing only. This is achieved by a low-overhead transaction consisting of the data receiver sending a *request-for-data* (RFD) frame and the data sender replying with a data frame.

We make two key contributions in this paper. First we present a new receiver-centric carrier sense technique in wireless ad hoc networks. The new design achieves maximized spatial reuse via accurate channel assessment to overcome exposed and hidden terminal problems. Furthermore, compared to previous approaches, RCS efficiently eliminates unnecessary overhead such as per-packet acknowledgement frames. Second, we evaluate the performance of RCS via both analysis and simulations. Our simulation evaluation results show that RCS outperforms the legacy receiver-centric protocols by up to 20.9%.

2. Related Work

Several *receiver-centric* solutions [6-8] have been proposed to solve the problems of sender centric carrier sense protocols. Multiple Access with Collision Avoidance By Invitation (MACA-BI) [6] improves the performance of the MACA protocol by *excluding the request to send (RTS) frame in* the RTS / clear to send (CTS) exchange, thus reduces the virtual carrier sensing overhead. But, it has been shown that MACA-BI suffers from severe hidden terminal problems [7]. Receiver Initiated Multiple Access with Simple Polling (RIMA-SP) [7] enhances MACA-BI by resolving the hidden terminal problem, but it still suffers from the exposed terminal problem. Receiver initiated MAC protocol based on multi-user detection (MUD) [8] attempts to reduce the signaling overhead in code division multiple access (CDMA) ad hoc networks. In essence, MUD is similar to RIMA-SP with an additional fair scheduling scheme.

3. Receiver-Centric Carrier Sense (RCS)

In this Section, we first discuss the fundamental limit of sender-centric carrier sense and present the details of RCS. In sender-centric physical carrier sensing (PCS) [3], the data sender typically senses a much larger range than the transmission range to avoid interference at the receiver. This induces the exposed terminal problem where nodes that actually do not interfere may have to defer their access. Sender centric virtual carrier sensing (VCS) [2,4] shows better spatial reuse since RTS/CTS frames prevent only the interferers from triggering transmissions. But the exchanges of RTS/CTS frames at the basic rate incur large overheads. To solve the problems of sender-centric carrier sense, several receiver-centric solutions [6,7] have been proposed. The main objective of these protocols is to reduce overhead by eliminating the RTS frame, so they still suffer from hidden [6] and exposed terminal problems [7]. For simplicity, we generally use the terms *sender* and *receiver* to denote the sender and receiver *of the data frame*, respectively.

We *next explain* how RCS solves both hidden and exposed terminal problems with minimal amount of overhead. RCS adopts a new control frame called *request for data* (RFD) that the receiver sends to a potential sender. A RFD frame (See Fig. 1) format is similar to that of the RTS frame [1], except for a 1-byte *RCS field*. RCS eliminates the ACK frames for efficiency purpose thus a transaction consists of RFD and corresponding DATA transmissions only. If the receiver fails to receive the corresponding DATA, then it reissues an RFD frame with the *retransmit bit* in the *RCS field* set, so that the sender can retransmit the DATA frame.

The RFD serves for another purpose to protect the receiver from interference. RCS employs two

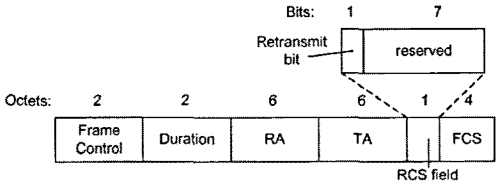


Fig. 1 Request-for-data (RFD) frame format

carrier sense thresholds, CS_{th_INT} and CS_{th_MIN}. CS_{th_INT} denotes the threshold that corresponds to the *interference range* [4], which is generally larger than transmission range. CS_{th_MIN} is the *minimum* carrier sense threshold and is consistent with the *maximum* carrier sense range, which is obviously larger than the interference range. When a neighbor node receives the RFD frame, it will defer its access according to the duration fields, which is similar to the virtual carrier sense procedure in 802.11 DCF. The difference is that even when a node fails to clearly decode the RFD frame, but instead senses the channel as busy using CS_{th_INT} for a unique RFD frame duration (84μs in 802.11a with 6Mbps), it will dynamically decrease its physical carrier sense threshold to CS_{th_MIN} until the channel becomes idle. By this method, the receiver can be protected from interference. We call this procedure VCS in RCS since it is similar to that of 802.11.

Before transmitting the RFD, the node will check for both PCS (using CS_{th_INT}) and VCS as explained above to prevent collisions due to the hidden terminal problem. Through VCS, it is insured that the receiver's RFD will not interfere with any ongoing receptions. The sender will transmit the DATA with only VCS, *not* PCS. Since VCS is employed, the sender will not interfere with other ongoing transmissions. As PCS is not used at the sender, the exposed terminal problem is solved.

Notice that in order to initiate transmission the receiver needs to know the sender's current transmit buffer state. There are number of ways to achieve this; First, one method is to incorporate the IEEE 802.11 ad hoc traffic indication message (ATIM) message [1] in RCS, and use this to announce transmit buffer existence. Another straightforward way is by periodic announcement of the transmit buffer state from the sender piggybacked in periodic hello messages. Various polling methods have been proposed in [7].

It is worth mentioning that these broadcast frames should be transmitted in a *sender-centric* manner by using CS_{th_MIN} even when RCS is employed for unicast data transmission. It is not practical to apply receiver-centric carrier sense to broadcast frames since there are usually multiple receivers for the broadcast frames.

4. Performance Analysis

In this section we derive an analytic model to study the network capacity of RCS and compare it with the legacy sender-centric carrier sense approach. The transmission power is fixed at P_{TX} so that the received power is modeled as $P_{RX} = P_{TX} / r^{\theta}$ where r is the distance between sender and receiver and θ is the *path loss exponent* which may range from 2 to 5 depending on the path loss model. The transmission range is R and the interference range is D.

For the network capacity of the legacy sender-centric carrier sense approaches, we use and restate the result in [3] for the comparison purpose. To derive the capacity of RCS, we consider a honey-grid topology with 6 interfering nodes shown in Fig. 2, where nodes are uniformly and independently distributed in a unit area of U [3]. The separation constraint for the RCS are enforced by placing all the concurrent receivers at least distance D away from any other receivers and transmitters. This honey grid is constructed by setting the distances between RX_0 and 6 transmitters (TX_1~TX_6) by at least D. Similarly, the distances between RX_1~RX_6 and TX_0 are also at least D.

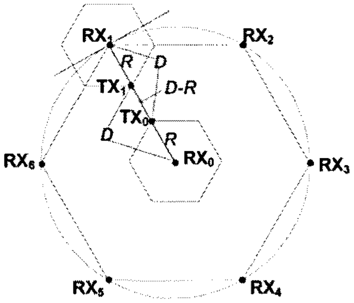


Fig. 2 Honey-grid topology with 6 interfering nodes

We first derive the average interference and Signal to Interference and Noise Ratio (SINR) at a receiver RX_0. Since the interference from the entire network is in the same order as the interference from the first tier nodes, we only consider the six first tier interfering senders $\{TX_1,\cdots,TX_6\}$. The interference at RX0 from the first tier interfering nodes can be expresses as follows

$$\overline{INT}=\sum_{i=1}^{6}\overline{INT_i}=\sum_{i=1}^{6}\frac{P_{TX}}{\overline{d_i}^{\theta}}<6\times\frac{P_{TX}}{(R+D)^{\theta}} \tag{1}$$

where $\overline{d_i}$ is the average distance between TX_i and RX_0. The above inequality holds since $\Pr\{d\le(R+D)\}<0.5$ so that $E[d]>(R+D)$. Therefore the worst case *SINR* at RX_0 is

$$SINR=\frac{P_{TX}/R^{\theta}}{\overline{INT}}>\frac{1}{6}\cdot(\frac{D+R}{R})^{\theta} \tag{2}$$

Assuming that the entire network area U is large enough to ignore the edge effect, an area of the parallelogram is consumed by four concurrent sender/receiver pairs. Therefore the network capacity T_N is expressed by the Shannon capacity [9] as,

$$T_N=(U/U_A)\cdot T_A=(U/U_A)\times B\cdot\log_2(1+SINR) \tag{3}$$

where $U_A=3\sqrt{3}\times(R+D)^2/2$ and B is the channel bandwidth. From (2) and (3), the next inequality holds

$$T_N<\frac{C_0}{X^2}\cdot\log_2(1+\frac{X^{\theta}}{6}) \tag{4}$$

where $X=(D+R)/R$ and C_0 is a constant.

We plot the capacity results of the two protocols in Fig. 3. We set and $B=20\text{MHz}$ and vary θ from 2 to 5 and obtain the maximum achievable normalized network capacity for a general topology of unit area 1m^2. For a given θ, there is an optimal value of X that maximizes the capacity for each cases. For all θ values, the maximum capacity of RCS is higher than that of legacy sender-centric carrier sensing mechanism by up to 61.6%, and 51.9% in average.

5. Simulations

In this section we study the impact of traffic load on the performance of RCS compared to both sender-centric 802.11 MAC [1] and MUD [8]. RIMA-SP [7] has been shown to outperform MACA-BI [6] since it prevents the hidden terminal problem, so we exclude the comparison with MACA-BI. Since RIMA-SP is basically an identical receiver-centric protocol with MUD, we only show the comparison with MUD.

The simulations are conducted in a 1000 × 1000(m) area. We use the physical and MAC specifications of IEEE 802.11a [10] and used fixed data rate of 24 Mbps for data frame transmissions. The number of randomly placed stationary nodes increases from 50 to 400. The transmission range is fixed at 100m. All data points are averaged over 20 runs of the experiment. Fig. 4 illustrates that both receiver-centric protocols (MUD and RCS) outperform the sender-centric IEEE 802.11. Since IEEE 802.11 conducts a very conservative carrier sensing approach to protect the receivers, it suffers from severe exposed terminal problems. RCS consistently outperforms MUD by up to 20.9% and 17.6% in average. Although MUD eliminates the RTS frame to reduce overhead and prevents the hidden terminal problem, it still suffers from the exposed terminal problem due to inaccurate channel assessment. RCS utilizes the highest level of spatial reuse by exploiting the most number of concurrent

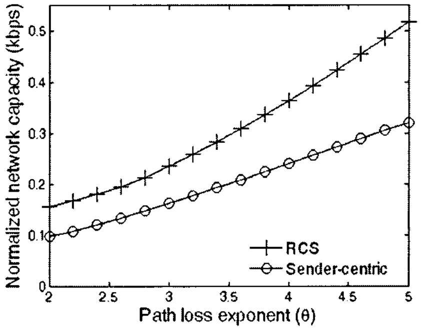


Fig. 3 Analytic results

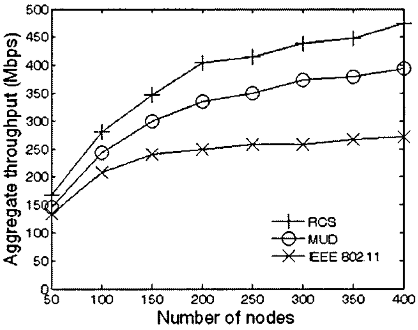


Fig. 4 Simulation results

transmissions, since RCS overcomes both hidden and exposed terminal problems via smart channel assessment. Furthermore, RCS eliminates unnecessary ACK frames to reduce overhead. Note that the receiver-centric approaches still outperform IEEE 802.11 even though they send periodic (one second) broadcasts of its current buffer state.

6. Conclusion

In this paper, we proposed a receiver-centric medium access control protocol called RCS. In RCS, both the receiver and sender make accurate channel assessment to prevent interference and maximize spatial reuse. We conducted both analysis and simulations to show that RCS outperforms legacy schemes in terms of throughput.

References

[1] IEEE 802.11. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE, Aug. 1999.

[2] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless LANs," Proc. of *ACM SIGCOMM'94*, 1994.

[3] X. Yang, N. Vaidya, "On the Physical Carrier Sense In Wireless Ad Hoc Networks," in Proc. *IEEE Infocom*'05, 2005.

[4] K. Xu, M. Gerla, and S. Bae, "How Effective is the IEEE 802.11 RTS/CTS Handshake in Ad Hoc Networks?," in Proc. of *IEEE Globecom*'02, 2002.

[5] K. Jamieson, B. Hull, A. Miu, H. Balakrishnan, "Understanding the Real-World Performance of Carrier Sense," In Proc. *ACM E-WIND*'05, 2005.

[6] F. Talucci, M. Gerla and L. Fratta, "MACA-BI (MACA by invitation) - A Receiver Oriented Access Protocol for Wireless Multihop Networks," in Proc. *IEEE PIMRC*'97, 1997.

[7] J.J. Garcia-Luna-Aceves and A. Tzamaloukas, "Receiver-Initiated Collision-Avoidance in Wireless Networks," *ACM Wireless Networks*, vol.8, pp. 249-263, 2002.

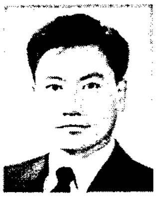
[8] J. Zhang, Z. Dziong, F. Gagnon, and M. Kadoch, "Receiver initiated MAC design for Ad Hoc networks based on multiuser detection," in Proc. *QShine'08*, 2008.

[9] T. Rappaport, "Wireless Communications Principle and Practice Second Edition," Prentice Hall 2002.

[10] IEEE Std. 802.11a, 802.11a-1999, 1999.

유준

1997년 KAIST 기계공학과 학사. 2009년 서울대학교 전기컴퓨터공학부 박사 2009년 서울시립대학교 컴퓨터과학부 연구교수. 2009년~현재 University of California, Los Angeles (UCLA) Post-doctoral Researcher. 관심분야는 무선 차량이동망, 무선랜



김종권

1981년 서울대학교 산업공학과(학사). 1982년 미국 조지아 공과대학교 산업공학과(석사). 1987년 미국 일리노이 대학교 전산학과(박사). 1984년~1987년 IBM 산호세 연구소 연구조원. 1987년~1991년 미국 Belcore 통신연구소 연구원. 1991년~현재 서울대학교 전기·컴퓨터공학부 교수. 관심분야는 차세대 인터넷, 초고속 라우터, 이동통신