Multi-channel Enhancements for IEEE 802.11-based Multi-hop Ad-hoc Wireless Networks†

YongSuk Lee[1], WoongChul Choi[1]*, SukJoong Kang[1], SeongJe Cho[2]
[1] Department of Computer Science
KwangWoon University
[2] Division of Information and Computer Science
DanKook University,
*wchoi@kw.ac.kr

Abstract. Collision avoidance is critical for the performance of contention-based medium access mechanism such as CSMA. In this paper, the IEEE 802.11-based MAC protocol is enhanced for performance improvements in multi-hop ad-hoc wireless networks. The protocol behavior of hidden terminals in carrier sensing range[10] is important for end-to-end performance. There are several mechanisms defined in IEEE 802.11 standard such as IFS(Inter Frame Space), but we address a problem that such time interval is not long enough to avoid unnecessary collisions by the hidden terminals in carrier sensing range. We have conducted a comprehensive simulation to study performance improvement. The simulation results indicate that the performance is increased and the number of the dropped packets due to unnecessary collisions can be significantly reduced as much as a half.

Keywords—*Ad-hoc wireless networks, IEEE 802.11, MAC, Collision, CAI(Collision Avoidance Interval)*

1 Introduction

In the IEEE 802.11-based MAC protocol[1], two medium access control protocols are specified - PCF(Point Coordination Function) and DCF(Distributed Coordination Protocol). DCF is often used as a referred scheme for multi-hop ad-hoc wireless networks, and is a contention-based medium access protocol - a host that has frames to send can send them only when the medium is available, which means it works in simplex mode. There are several research works to overcome this limitation[7][8][9].

The range covered by the power necessary for transmitting a frame has two disjoint areas, named transmission range and carrier sensing zone (Fig. 1)[10]. In transmission range, a node can sense and decode a signal correctly, whereas a node can sense but can not decode it correctly in carrier sensing zone. To avoid a collision, a

---

† This work was supported by the Korea Science and Engineering Foundation(KOSEF) grant funded by the Korea government(MOST) (R01-2005-000-10934-0) and by the Research Grant of KwangWoon University in 2007

* Corresponding author

node is required to sense the medium first before transmitting a frame. If it finds the medium busy, the behavior of the node in IEEE 802.11 specification is as follows. If the node is in transmission range, it can decode the signal correctly, so it can also recognize NAV(Network Allocation Vector) which indicates the remaining time of on-going transmission sessions, therefore, it defers transmitting a frame during that NAV interval. But if it is in carrier sensing zone, the node can not decode the signal, so it can not recognize NAV.

In this paper, we address the importance of the protocol behavior in carrier sensing zone and show that the behavior is required to be modified to avoid unnecessary collisions to improve performance. With these modifications on MAC protocol, we show how significantly the performance improves by both in-depth analysis of the protocol behavior and simulation. We use the term of packet and frame interchangeably in this paper, although the former is usually used for layer 3 terminology, and the latter for layer 2[14], and if the distinction is required, it will be clarified in the context.

The rest of this paper is organized as follows. In Section 2, we review the related works. We provide the problem statements in Section 3 and detailed description of our solution in Section 4. In Section 5 and 6 discusses simulation and the results. We conclude the paper in Section 7.

2 Related Works

There have been many research efforts to improve the performance of the IEEE 802.11-based wireless networks. The efforts can be categorized into the collision avoidance in terms of power control for transmitting a packet, hidden/exposed terminal problem and how to handle a collision. Jung *et al.* [10] propose a power control protocol where MAC protocol uses a maximum power level for RTS-CTS and a minimum power level for DATA-ACK, combined with using a maximum power level for DATA periodically to avoid any potential collision and show the throughput and power saving improvement. Fujii *et al.* [11] propose a MAC protocol where a high-power node forwards the RTS and CTS packets from a low-power node to improve success rate performance of a data, by reducing collisions that occur after connection establishments, regardless of the size of the transmission range. Dutkiewicz [12] tries to find out the optimum transit range to maximize data throughput in ad-hoc wireless networks. The author presents a simulation study that under a wide set of network and load conditions multi-hop networks have lower performance than single-hop networks, data throughput is maximized when all nodes are in range of each other and also shows that the addition of relay-only nodes does not significantly improve throughput performance of multi-hop networks. Bharghavan *et al.* [5] investigate a hidden/exposed terminal problem in a single channel wireless LAN. They modify the basic binary exponential backoff algorithm for fair use of bandwidth. They examine the basic RTS-CTS-DATA message exchange, classify the hidden/exposed terminal problem in four cases and propose solutions for each case. In

[9], Bharghavan proposes Dual Channel Collision Avoidance (DCCA), which employs two channels for signaling and data in order to avoid collisions efficiently in all cases of hidden/exposed receivers and senders, and Fair Collision Resolution Algorithm (FRCA), which seeks to fairly resolve collisions with both consideration for spatial locality of stations and back-off advertisement, in order to provide better channel utilization and delay properties compared to IEEE 802.11 standard. Cali *et al.* [6] propose a method that estimates the number of active stations via the number of empty slots, and exploit the estimated value to tune the contention window value based on their analytic model. Kwon *et al.* [3] propose a fast collision resolution(FCR), which actively redistributes the backoff timer for all competing nodes, thus allowing the more recent successful nodes to use smaller contention window and allowing other nodes to reduce backoff timer exponentially when they continuously meets some idle time slots, instead of reducing backoff timer by 1 after each idle time slots, as in the original IEEE 802.11 DCF. FCR can resolve collisions more quickly than 802.11 DCF. Lin *et al.* [4] propose a mechanism called distributed cycle stealing for improving the performance of DCF protocol of 802.11. They investigate the issue of efficient channel utilization, where all the communications should obey power-distance constraints, which guarantee that all transmissions would not disturb each other during all communication periods. Acharya *et al.* [8] propose the Data-Driven Cut-Through Medium Access(DCMA) protocol, which combines the ACK to the upstream node with the RTS to the downstream node in a single ACK/RTS packet to reduce collision and forwarding latency.

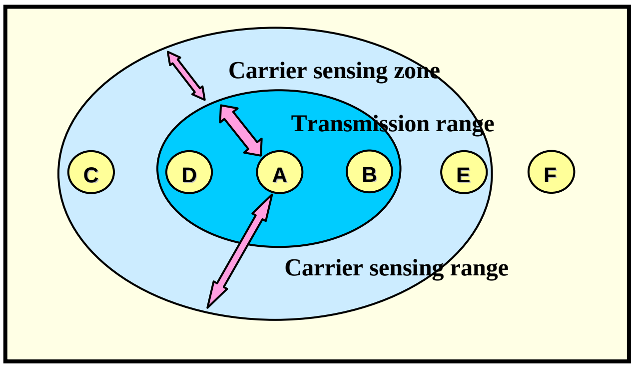

Fig. 1 Two disjoint areas of carrier sensing zone and transmission range, both of which constitute the carrier sensing range for node A. We assume that node A is a sender and node B is a receiver and transmission range from a frame transmitting source is one hop and carrier sensing rage is two hops. Then node C and E is said to be in carrier sensing zone of the sender side.

3 Problem Statement

Consider a simple fixed chain topology like Fig. 1. Assume that node A is a sender, node B is a receiver and all the other nodes have data frames to send. Suppose that node A initiates a frame transmission to node B with RTS-CTS-DATA-ACK mechanism. Fig. 2 shows how 802.11 protocol proceeds for each node and how collision occurs

In that situation, node D is in transmission range when node A sends RTS to node B. Likewise, node E is in transmission range when node B answers CTS to node A. Therefore, both nodes D and E can decode the NAV specified in RTS and CTS correctly, so they defer transmitting their frames during NAV interval(Phase I and II, III). However, since node C and node F are in sensing zone, they can not decode NAV field in RTS and CTS frame. In such case where a node senses a signal but can not decode it, IEEE 802.11 specifies that the node set NAV for EIFS(Extended Inter-Frame Space). So node C and node F set NAV after sensing respective signals(Phase I and II). After that, their behavior and the aftermath differ. Now node A starts transmitting a DATA frame, which can be sensed by node C, but not by node F(Phase III). For node C, this sensing happens before NAV expires, so it defers its frame transmission again. As a result, node C waits until a frame transmission from A to B ends. However, for node F, after NAV expires, it can not sense any signal at all, so it finds the medium idle and proceeds to the operation to send a DATA frame, i.e. switches to its state to contention mode. If it tries to transmit a frame, then a collision should occur(Phase III).

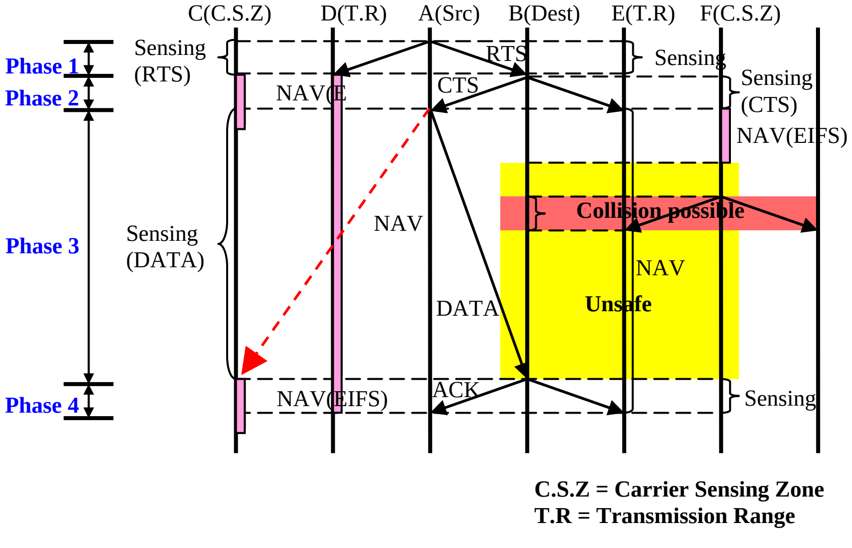

Fig. 2 Collision due to short NAV(EIFS)

As shown in Phase III(Fig. 2), when node F tries to transmit a frame after EIFS, then collision with node B always occurs, which results in discarding the DATA frame that node B is receiving. Once collision occurs for a DATA frame, the sender (node A) will increase contention window and execute the binary backoff process of data link layer and then tries to transmit that frame again. Contention window starts from 32-aSlotTime[1], and the next contention window size is 64-aSlotTime, and so on, therefore, the next retransmission will happen during the interval of [0, 1280μs], which is still too short for a successful frame transmission. Considering wireless networks where the end-to-end performance is inherently poor and where transmitting in half-duplex mode is one of generic properties, a frame loss due to collision greatly affects not only performance but also energy efficiency in negative way. In addition, if the lost frame is for a TCP connection, it results in packet loss. This, in turn, will increase the size of the contention window of TCP layer and the binary backoff mechanism of TCP layer will be executed at the source node. These sequences of TCP will negatively affect the end-to-end performance as well, and it is obvious that the consequence will become worse as the number of connections and the capacity of the transmission increases.

One possible solution is to increase the value of aSlotTime such that the contention window size is set to a larger value than the transmission time between the two nodes[3][13]. However, considering the property of ad-hoc networks where nodes can move any time so the topology always changes, it is not an ultimate solution. And also, even in fixed ad-hoc wireless networks, the relative role of a node continuously changes. For example, in Fig. 1, the role of the sender and the receiver changes if the direction of a flow of a connection changes, for example, in bi-directional connections.

From these reasons, protocol behavior should be different for a node in transmission range and in carrier sensing zone.

4 Protocol Improvements

We first make one assumption for protocol improvements that the nodes in carrier sensing zone can know the types of a frame. Even though this assumption might be arguable, because the nodes in sensing zone can not decode signal correctly from the definition(Fig. 1), there are a good solution for assumption. To know the types of a frame which is received in carrier sensing zone, we use multi-channel scheme. Specifically, the IEEE 802.11 in ad hoc mode, the most popular MAC protocol in mobile ad hoc networks, is extended from single channel to multiple channels operation[14]. The current standard allows the practical use of three channels in 802.11b and eight in 802.11a, but multiple channels operation is not supported in ad hoc mode.

A. *Transmission on Multi-channel*

Among the channels that are able to be used simultaneously, channel 0 is reserved for RTS and CTS frame, channel 1 is reserved for DATA frame, and channel 2 is reserved for ACK frame. Fig 3 shows the frame exchange between sender and receiver on multi-channel.

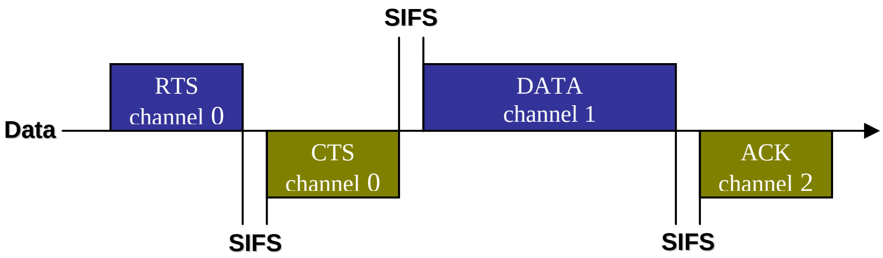

Fig. 3 Frame exchange between sender and receiver on multi-channel

Using multi-channel, nodes in carrier sensing zone can recognize the types of a frame exactly.

B. *CAI (Collision Avoidance Interval)*

Now we describe our MAC protocol improvements in detail. We first define a term *CAI*(Collision Avoidance Interval). *CAI* is defined for a node in carrier sensing zone and is defined as a time interval from the moment when the node in carrier sensing zone senses CTS signal in channel 0 until the node senses ACK signal in channel 2. Therefore, it is time interval necessary for exchanging DATA and ACK frame between a transmitting node and a receiving node. From the motivation in the previous section, NAV, which is set to EIFS in IEEE 802.11, is too short for collision to be prevented, so we use *CAI* instead of NAV. While *CAI*, the node defers transmitting a frame, like in NAV, even when the node has a frame to send. But there are two important differences in the protocol behavior. The first difference is that the node resets to *CAI* whenever it senses another CTS signal while in carrier sensing zone, so it can be repeatedly set to *CAI*. The reason for this is because of ad-hoc networking property-nodes can move anytime, so the relative location and the role of a node continuously changes. Even in fixed ad-hoc wireless networks, signals can be received from any direction. The second difference is that the node in *CAI* can answer to RTS frame from other nodes. The reason for this is to improve performance if the node moves out from the carrier sensing zone.

Because of the node mobility, the node which received CTS signal and started *CAI* can not receive ACK signal. Therefore, it is necessary to define the minimum length of *CAI*. In 802.11 specification, there are two parameters related to DATA frame size, RTS threshold and Fragmentation threshold. If a DATA frame size is upper the RTS threshold, RTS-CTS is used. If a DATA frame size is upper the Fragmentation threshold, a frame is transmitted using fragmentation. Therefore, the size of all transmitting DATA frame using RTS-CTS is under the Fragmentation threshold. We define the length of *CAI*, *CAI_threshold* as follows.

- *txtime*(x) = transmission time for the frame x
- *CAI_threshold* = Fragmentation threshold + SIFS + *txtime*(ACK)

```
/* protocol behavior state
            when sensing CTS or ACK */

CAIThreshold = FragThreshold + SIFS
                          + txtime(ACK);

if (CTS or ACK sensing in channel 0) {
   if (during backoff) pause backoff_timer;
       start CAI;
       CAI_timer start;
}
else if (ACK sensing channel 2) {
  stop CAI ;
  if (is_channel_idle()) {
       if (backoff_timer_paused)
                          resume backoff_timer;
       else {  wait for EIFS;
            proceeds to normal operation;
       }
  }
else  {  /* 802.11 basic operation */
      if (backoff_timer_paused)
                         resume backoff_timer;
      else  start backoff_timer;
      }
  }
}
/* Function when the CAI_timer expired */

CAI_timer_handler()
{
      if(during CAI){
          stop CAI;
 /*back to the normal operation of 802.11
MAC protocol*/
      }
}
```

Fig. 4 *CAI* and the procedure for MAC protocol improvements

From the above description on the modification, the cost for the misinterpretation of frame type is a waste of *CAI* only. In Fig. 4, the procedure for MAC protocol improvements is presented and commentated. Notice that the value of *CAI* is automatically tuned to the length of current data frame. Fig. 5 shows how collision is prevented by *CAI* and the new procedure. Comparing to Fig. 2, the unnecessary collision by node F is prevented.

Fairness for the probability of a frame being transmitted is important in ad-hoc wireless networks. In the 802.11 specification, after a frame transmission has completed, every node may attempt to transmit a frame in contention mode. The probability of a transmission changes according to the retry count. For example, a node that has retry count 2 has higher probability than a node that has retry count 3. But a node in *CAI* has less chance than a node in normal state, because the node in *CAI* defers its transmission. Although being applied by *CAI*, a node that has retry count 2 has to have higher probability than a node that has retry count 3. In our simulation, *CAI* can start only when the retry count is under 3. The reason for this is that the length of *CAI* for 1Kbytes data frame is 4697us under 2Mbits/s and this length is almost equal to the backoff time for a node in retry count 3.

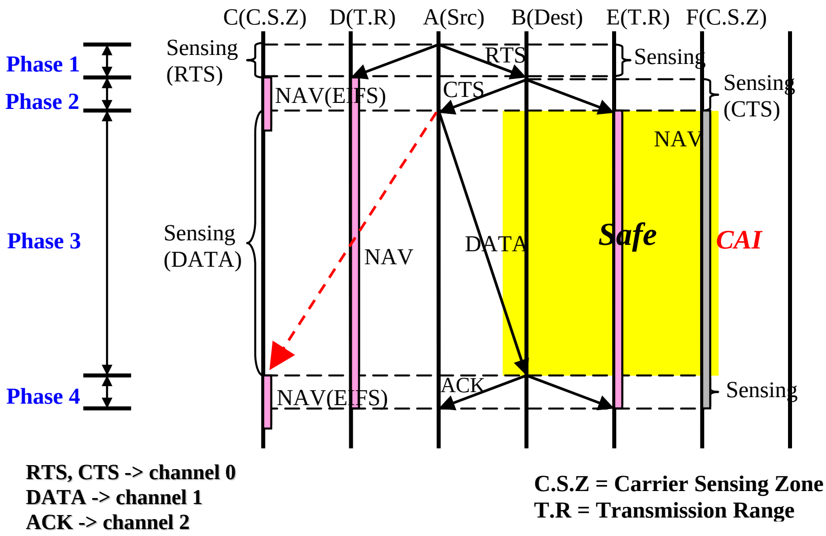

Fig. 5 *CAI* and Collision prevention

5 Simulation

We have implemented the proposed protocol improvements in *ns-2*[15] and conducted a comprehensive study to evaluate the performance enhancements of 802.11-based multi-hop ad-hoc wireless networks. The main metrics for performance evaluation are end-to-end throughput, the number of collisions, the number of drops and power consumption. We perform simulations for tcp and udp bidirectional connections. The number of connections is 12, the network size is 1000 x 1000(m^2), and the number of mobile nodes is 56. *CAI* is set to the length of (Fragmentation Threshold + SIFS + transmission time of ACK frame) to allow one virtual DATA frame transmission. The length of a DATA frame is assumed to be 0.5, 1, 1.5 Kbytes. In order to minimize the interference from a routing protocol, DSDV(Destination Sequenced Distant Vector) routing protocol is used. DSDV[2] is one of the proactive routing protocols and the route update packets are sent periodically and incrementally as topological changes. The performance values are evaluated after running simulations for 300 *ns-2* simulation seconds. The simulations are conducted on Linux 2.4.20 on a Pentium 3.0 Ghz PC with 516Kbytes main memory. The version of *ns-2* is *ns-2.27*.

6 Results

Fig. 6 shows the simulation results of end-to-end throughput for 12 bidirectional tcp and udp connections. Fig. 6 shows that throughputs by our modified protocol always performs better.

Fig. 7 shows the comparisons of the number of collisions for both tcp and udp connections. In Fig. 7, the number of collisions represents the number of frame loss at every hop and is significantly reduced as much as 20% for both tcp and udp connections. In fact, this reduction in the number of collisions is the most outstanding feature of our modified protocol.

Fig. 8 shows the comparisons of the number of drops for tcp and udp connections. In 802.11, when a node transmits a frame, it must receive an acknowledgement from the receiver or it will consider the transmission to have failed. Failed transmissions increment the retry counter associated with the frame. If the retry limit is reached, the frame is discarded. In Fig. 8, the number of drops represents the number of discarded frame by retry limit excess at every hop. This number is important in TCP performance, because drop by retry limit excess means end-to-end loss and TCP think this drop as congestion loss. Therefore, to improve TCP end-to-end performance, it is important to reduce the number of drop by retry limit.

Table. 2 and 3 show the comparisons of the power consumption for tcp and udp connections. When *CAI* is applied in a node, the overhead for power consumption is given by 10%, 30%, 50%, 100%. In table. 2 and 3, while the total power consumption grows, the power consumption for sending 1Mbytes is reduced.

6 Conclusion

In this paper, we addressed the importance of the protocol behavior in carrier sensing zone to prevent unnecessary collisions, and showed that the protocol behavior is required to be modified by in-depth analysis of the protocol behavior. We defined a term *CAI* to avoid unnecessary collisions and this interval is used for a node in carrier sensing zone instead of NAV when the node senses CTS signal. We conducted a comprehensive simulation study to examine how the performance of the modified protocol in multi-hop wireless ad-hoc networks works. Our improved MAC protocol is completely compatible with the IEEE 802.11 specification, so it can be coexistent with the legendary 802.11-based wireless MAC protocol. With the improvements in the MAC protocol, the number of collisions and the number of drops are decreased as much as 20% and the throughput is as much as 8% for 300 simulation seconds. As a result, we can verify that the end-to-end performance is significantly improved by our MAC protocol enhancements.

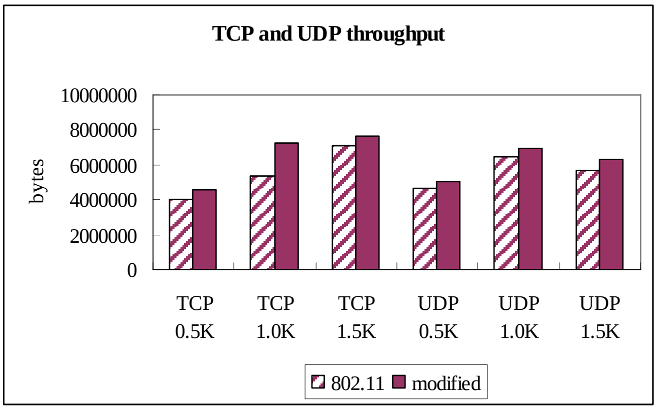

Fig. 6 TCP and UDP throughput evaluation

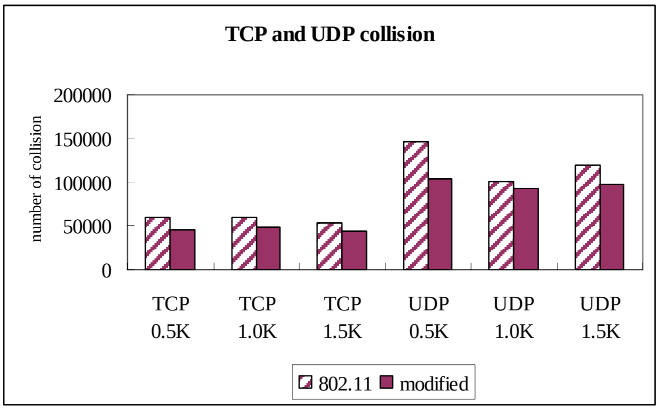

Fig. 7 TCP and UDP collision evaluation

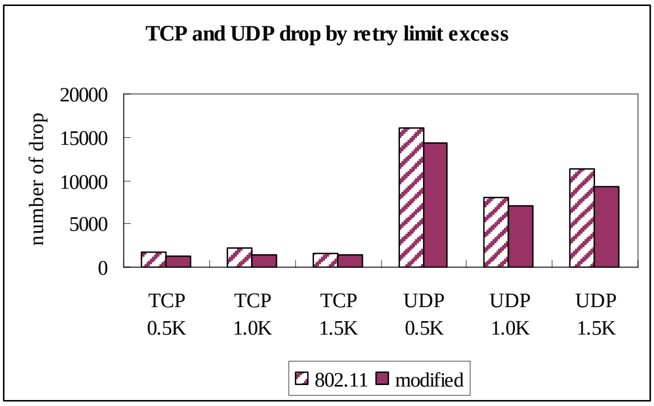

Fig. 8 TCP and UDP drop by limit excess

	802.11	O.H 0%	O.H 10%	O.H 30%	O.H 50%	O.H 100%
Idle power consumption	**1855(w)**	**1750(w)**	**1750(w)**	**1750(w)**	**1750(w)**	**1750(w)**
Send power consumption	**169(w)**	**171(w)**	**171(w)**	**171(w)**	**171(w)**	**171(w)**
Recv power consumption	**2833(w)**	**3144(w)**	**3144(w)**	**3144(w)**	**3144(w)**	**3144(w)**
Power consumption by process-ing overhead	**0(w)**	**26.45(w)**	**29.10(w)**	**34.39(w)**	**39.68(w)**	**52.91(w)**
Total power consumption	**4857(w)**	**5093(w)**	**5096(w)**	**5101(w)**	**5106(w)**	**5119(w)**
Power consumption for sending 1Mbytes	**0.9297(w)**	**0.7210(w)**	**0.7215(w)**	**0.7222(w)**	**0.7229(w)**	**0.7247(w)**

Table. 2 Power consumption for TCP 1.0K traffic

	802.11	O.H 0%	O.H 10%	O.H 30%	O.H 50%	O.H 100%
Idle power consumption	**1657(w)**	**1648(w)**	**1648(w)**	**1648(w)**	**1648(w)**	**1648(w)**
Send power consumption	**217.8(w)**	**217.6(w)**	**217.6(w)**	**217.6(w)**	**217.6(w)**	**217.6(w)**
Recv power consumption	**3402(w)**	**3430(w)**	**3430(w)**	**3430(w)**	**3430(w)**	**3430(w)**
Power consumption by process-ing overhead	**0(w)**	**14.87(w)**	**16.36(w)**	**19.33(w)**	**22.30(w)**	**29.74(w)**
Total power consumption	**5278(w)**	**5311(w)**	**5313(w)**	**5316(w)**	**5319(w)**	**5326(w)**
Power consumption for sending 1Mbytes	**0.8385(w)**	**0.6438(w)**	**0.8441(w)**	**0.8446(w)**	**0.8450(w)**	**0.8462(w)**

Table. 3 Power consumption for UDP 1.0K traffic

References

1. IEEE "IEEE Standard for Wireless LAN-Medium Access Control and Physical Layer Specification", IEEE 1997
2. Perkins, C., Bhagwatt, P., "Highly Dynamic Destination-Sequenced Distance-Vector Routing for Mobile Computers", Computer Communications Review, Oct. 1994, pp. 234-244
3. Y. Kwon, Y.Fang, and H.Latchman, "A novel MAC protocol with fast collision resolution for wireless LANs," IEEE INFOCOM 2003, Apr, 2003.
4. Lin, C.R., Chien-Yuan Liu, "Enhancing the performance of IEEE 802.11 wireless LAN by using a distributed cycle stealing mechanism", IEEE International Workshop on Mobile and Wireless Communications Network 2002, pp. 564-568
5. V.Bharghavan, A.Demers, S.Shenker, L.Zhang, "MACAW: Media Access Protocol for Wireless LAN's, Proceedings of SIGCOMM 1994, pp. 212-225
6. F.Cali, M.Conti, E.Gregori, "IEEE 802.11 protocol design and performance evaluation of an adaptive backoff mechanism", IEEE Journal of Selected Areas in Communications, vol. 18, no. 9, 2000
7. J.P.Monks, V.Bharghava, W.-M.W.Hwu, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks", IEEE INFOCOM 2001
8. Acharya, A., Misra, A., Bansal, S., "A Label-Switching Packet Forwarding Architecture for Multi-hop Wireless LANs, ACM WowMom, 2002
9. V.Bharghavan, "Performance Evaluation of Algorithms for Wireless Medium Access", Proceedings of IEEE International Computer Performance and Dependability Symposium, 1998
10. Eun-Sun Jung, Vaidya, N.H., "An energy efficient MAC protocol for wireless LANs", IEEE INFOCOM 2002
11. Fujii, T., Takahashi, T., Bandai, T., Udagawa, T., Sasase, T., "An efficient MAC protocol in wireless ad-hoc networks with heterogeneous power nodes", Wireless Personal Multimedia Communications, 2002
12. Dutkiewicz, E., "Impact of transmit range on throughput performance in mobile ad hoc networks", IEEE ICC 2001
13. Vitsas, V., "Throughput Analysis of Linear Backoff Scheme in Wireless LANs", IEE Electronics Letters, pp. 99-100, Vol. 39, No. 1, 2003
14. Nakjung Choi, Yongho Seok, Yanghee Choj, "Multi-channel MAC protocol for mobile ad hoc networks", Vehicular Technology Conference, 2003, VTC 2003-Fall 2003 IEEE 58th, Volume:2, 6-9 Oct. 2003
14. http://www.cisco.com
15. http://www.isi.edu/nsnam/ns/