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Full Length Research Paper

The development of enhancing mechanisms for improving the performance of IEEE 802.15.4

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There has been increasing interest in wireless network system in recent years, yet there are many issues to be resolved, mainly on topics related to its application design, such as the field of robot, artificial intelligence, and healthcare system etc. IEEE 802.15.4 is a standard protocol needed to achieve the low cost, low power consumption and low data rate Low-Rate Wireless Personal Area Network (LR-WPAN) widely used in remote metering, building automation, toys, smart tags, industry control, etc. The IEEE 802.15.4 protocol specifies the inclusion of a physical layer (PHY) and Medium Access Control (MAC) sub-layer for LR-WPAN. The PHY contains three different frequency bands comprised of 27 radio frequency channels. The MAC sub-layer handles all access to the physical radio channel. The MAC protocol controls potential contention and collisions but the slotted CSMA/CA algorithm cannot effectively avoid collisions in IEEE 802.15.4. Therefore, the transmission performance is affected. Most current research is focused on reducing power consumption, the development of enhanced routing approaches and the like. Studies focused on reducing collision problems are rare. In this study, two novel hash channel selection mechanisms for improving performance of IEEE 802.15.4 are proposed. Meanwhile, a star topology is constructed for simultaneous simulation and evaluation of the hash mechanism using NS-2 simulations. The results of the simulation reveal that the proposed hash mechanisms offers improved throughput, utilization, average delay and drop-off performance in all respects for IEEE 802.15.4 by about 100%.

Keywords: IEEE 802.15.4, MAC, Hash channel selection, Transmission performance

INTRODUCTION

Some issues of wireless network system are urgent, such as the field of robot, artificial intelligence (Chen et al., 2006, 2007), mechanical systems (Chen et al., 2007, 2006, 2009) and healthcare system (Lee et al., 2010, 2010) etc. The IEEE 802.15.4 is a standard protocol for Low-Rate Wireless Personal Area Networks (LR-WPAN). The IEEE 802.15.4 LR-WPAN working group is defined by a physical-layer and MAC-layer standard. Its low complexity, low cost and low power consumption make it suitable for low data rate wireless connectivity among inexpensive fixed devices. It is widely used in remote metering, building automation, toys, smart tags, industry control and so on. Recently, IEEE 802.15.4 has become standard with respect to ubiquitous networking and medical applications as noted in (Zheng and Lee, 2004; Golmie et al., 2005). The medium access control (MAC) protocol is important for transmission on wireless networks which must rely on a common radio medium. A MAC protocol is designed to deal with potential conflict and collisions in the communication medium. In (Misic et al., 2006; Misic et al., 2005; Chowdhury et al., 2009) some possible performance issues related to the MAC layer are presented. It is shown in (Krishnamachari and Raghavendra, 2004) that when there are multiple nodes, the performance will decrease because of collisions. In addition, the slotted CSMA/CA algorithm cannot effectively avoid collisions on IEEE 802.15.4 which affects the transmission performance.

Most current research has been focused on reducing power consumption, the development of enhanced routing approaches and so on. The MAC protocol plays an important role in determining the efficiency of the channel

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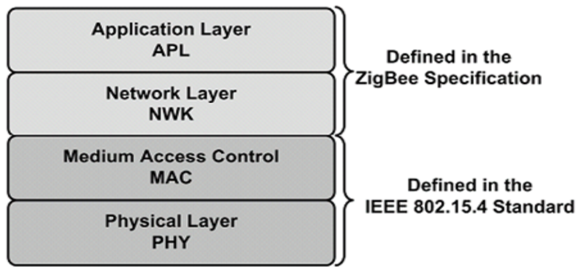


Figure 1. IEEE 802.15.4 protocol stacked architecture (IEEE, 2003).

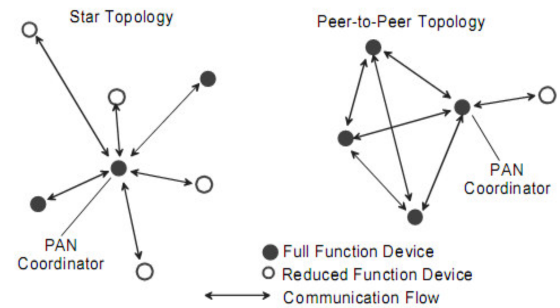


Figure 2. Examples of star and peer-to-peer topologies (IEEE, 2003).

bandwidth and energy consumed during communication. There has been some work done on the evaluation of the MAC protocol in IEEE 802.15.4 for use in a beacon-enabled network (Krishnamachari and Raghavendra, 2004; Ramachandran et al., 2007; Pollin et al., 2008). However, how to reduce the collision problem has not often been discussed. Here we propose and evaluate a hashing mechanism for use in the MAC layer. A novel hashing channel selection mechanism is proposed for improving the performance of IEEE 802.15.4. A simulation shows an improvement in the throughput, utilization, average delay and drop-off of the hash mechanism evaluated for a simple star topology. The simulation results are compared with those from the original protocol based on NS-2 simulations.

LITERATURE REVIEW

IEEE 802.15.4

The IEEE 802.15.4 is a standard protocol for Low-Rate Wireless Personal Area Networks (LR-WPAN). Its main features are network flexibility, low data rate, low cost and very low power consumption, which make it suitable for an ad-hoc network between inexpensive fixed, portable and moving devices. The IEEE 802.15.4 protocol includes a physical layer (PHY) and Medium Access Control (MAC) sub-layer for the LR-WPAN. The physical layer offers three operational frequency bands; there are a total of 27 channels allocated in the 802.15.4 range, with 16 channels in the 2.4 GHz band, 10 channels in the 915 MHz band, and 1 channel in 868 MHz band (IEEE 802.15.4 Standard, 2003).

The MAC sub-layer handles all access to the physical radio channel (IEEE 802.15.4 Standard, 2003). It provides an interface between the service specific convergence sub-layer (SSCS) and the PHY layer. A snapshot of the IEEE 802.15.4 protocol architecture is presented in Figure 1. The mechanisms proposed in this study are evaluated in the MAC layer.

Two different types of device can participate in an 802.15.4 network; a full function device (FFD) and a reduced function device (RFD). The FFD can operate in three modes: as a personal area network (PAN) coordinator, a coordinator or a device [15]. An FFD can talk to RFDs and other FFDs, but an RFD can talk only to an FFD. A network should include at least one FFD, operating as the PAN coordinator.

An IEEE 802.15.4 network operates either in a beacon-enabled mode or in a non-beacon-enabled mode (IEEE 802.15.4 Standard, 2003). In the beacon-enabled mode, communication is controlled by a network coordinator, which transmits regular beacons for synchronization and association procedures. In the non-beacon-enabled mode, there are no regular beacons, but the coordinator may unicast beacons to a soliciting device (IEEE 802.15.4 Standard, 2003). Only the beacon-enabled mode is considered in this study.

The standard allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator. A superframe consists of a contention access period (CAP) and contention free period (CFP). The CAP starts before the CFP on a superframe. A slotted CSMA-CA mechanism is used for all frames in the CAP. In addition, no transmissions within the CFP shall use a CSMA-CA mechanism.

An IEEE 802.15.4 LR-WPAN may operate in either of two topologies: a star topology or a peer-to-peer topology. Both are shown in Figure 2. In the star topology, communication is established between devices and the PAN coordinator. In the peer-to-peer topology, any device can communicate with any other device as long as they are in range of one another. The peer-to-peer topology also has a PAN coordinator. In this work 40 nodes are randomly arranged in a star network topology with a square area where the topologies are used for simulation to evaluate the throughput, utilization, average delay and drop-off.

Hashing

The hashing search method is different from general search methods. Hashing is a technique used for performing insertions, deletions, and finding a constant

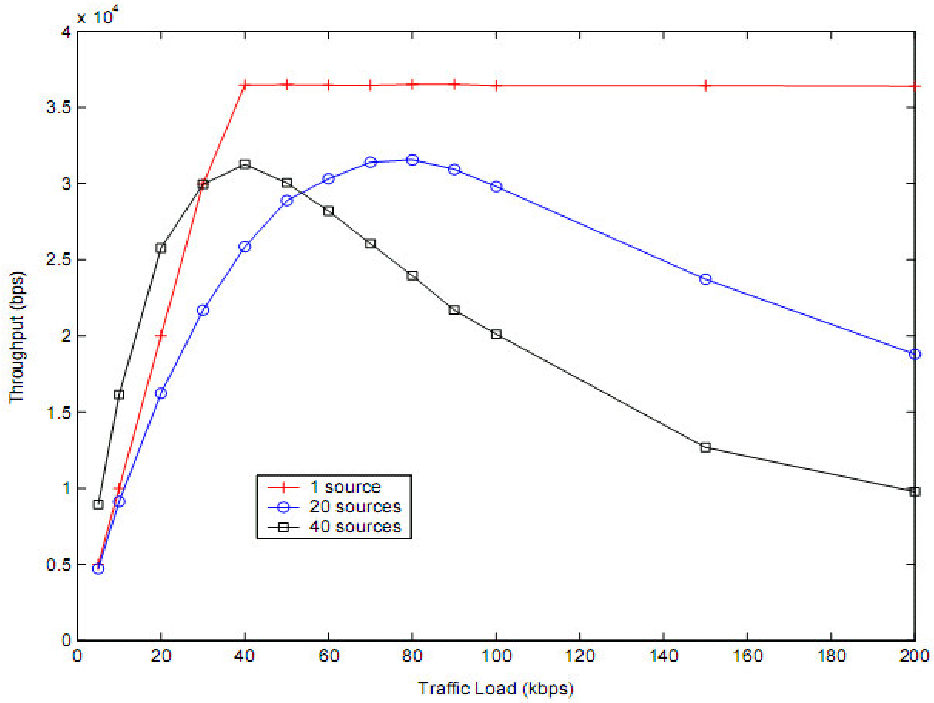


Figure 3. Throughput of CSMA-CA in beacon-enabled IEEE 802.15.4 (Lu et al., 2004)

average time (Weiss,1999). Hashing utilizes hash tables and hash functions. The hash table is a searchable container. Its interface provides methods for putting an object into the container, fining an object in the container, and removing an object from the container (Preiss, 1999). A function that transforms a key into a table index is called a hash function. To choose an ideal hash function is very important. An ideal hash function is easy to compute and approximates a random function. The result of hashing must attempt to avoid hashing multiple keys to the same location. The hash functions chosen should not only be easy to compute, but it is most desirable that the number of collisions be minimized. The hash function is designed to decrease the number of collisions and searching time.

Hashing comprises static and dynamic hashing. Static hashing is carried out to fit a hash table of fixed size, whereas dynamic hashing fits a hash table of dynamic size. Since the number of total channels in IEEE 802.15.4 is fixed, only static hashing is considered in this research. Hashing is a popular and effective method. Hashing applications are abundant in compilers, graph theory, network security, cryptography, and so on.

Performance evaluation of IEEE 802.15.4

Lu et al. (2004) discussed simulation-based performance evaluations of a medium access protocol in IEEE 802.15.4. They focused on a beacon-enabled mode for a star-topology network (Krishnamachari and Raghavendra, 2004). As can be seen in Figure 3, the performance will decrease because of collisions when there are multiple nodes. Shih et al. (2011) proposed novel mechanisms to improve the problem of channel selection. One of these mechanisms is the Scan First 3 Channels (SF3C); the other is the Random Prime Double Hash (RPDH). SF3C can resolve the high overloading problem of the PAN coordinator, but the mechanism may waste time on channel searching. RPDH can effectively avoid the collisions caused by repeated channel selection within a short period to reduce the occurrence of channel collision Shih et al., 2011). The simulated throughput of SF3C, RPDH and the original protocol are shown in Figure 4.

RESEARCH METHOD

Two novel hash mechanisms are proposed for improving performance of IEEE 802.15.4. Each of them is described as follows.

Random method

In general, random method is used when a collision occurs. In this research, the random method is different from original. The proposed mechanism uses a random prime generator to produce the random channel before

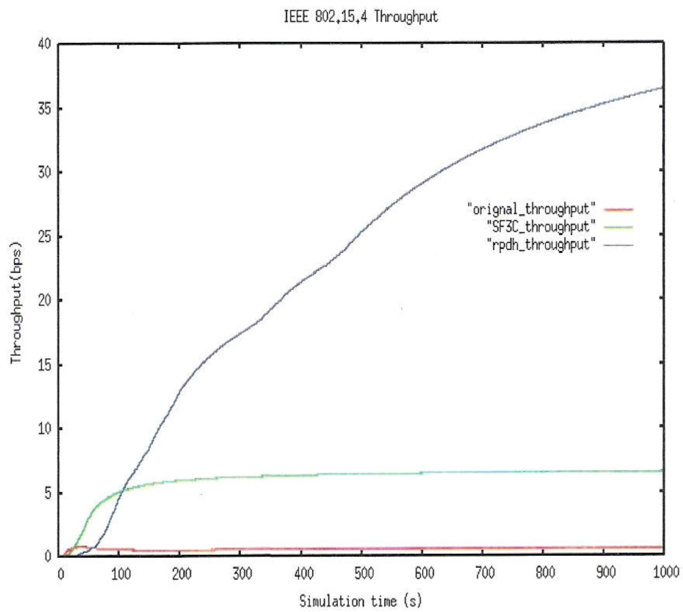


Figure 4. Throughput of Double HASH and SF3C (Shih et al., 2011)

the channel be assigned. This hash mechanism starts to allocate the channel before any device wants to send packets. 46 primes between 1 and 200 are defined. The results of hashing can be different if the key is a prime.

Enhanced linear probing

The simplest collision resolution strategy in hashing is linear probing. In linear hashing, alternative next slots well try until an empty cell is found when a collision occurs. If the end of the table is reached and no empty slot has been found, the search will be continued from the beginning of the table. However, linear probing may cause primary clustering. It means that any key hashed into the cluster will require several attempts to resolve the collision.

In this study, enhanced linear probing is improved to skip positions. This mechanism uses a random number generator to find the next available channel.

PERFORMANCE EVALUATION

Simulation environment

The proposed hash mechanism for improving performance of IEEE 802.15.4 is implemented and verified using an NS-2 simulator. The simulation environment is based on the IEEE 802.15.4 NS-2 module developed by J. Zheng in (Zheng and Lee, 2004). The IEEE 802.15.4 protocol stack consists of the physical layer (PHY) and a Medium Access Control (MAC) sub-layer. Our proposed mechanism is evaluated in the MAC layer.

Table 1. Simulation parameters.

Parameters	Values
Traffic	FTP
Packet Size	1000 bytes
Data Rate	250 kbps
Beacon Order	1
Superframe Order	1
Simulation Time	1000 seconds

The network topology used in the simulation is randomly and squarely assigned with 40 nodes. The topology is 50 × 50 m in area. An FTP traffic mode is used in the simulation. Parameters are set in tcl of NS2 are shown in Table 1.

Topology and evaluation functions

The topology of the original NS-2 IEEE 802.15.4 module is randomly overlapped in 40 nodes. The random topology developed and implemented to evaluate the performance of IEEE 802.15.4 is shown in Figure 5. The topology has 40 randomly assigned with a PAN (Personal Area Network) coordinator at the center of it. In general, the device should be located in the same position for a long time; hence the simulation time should be long. Thus, the simulation time is set to 1000 seconds. In Figure 6, Topology B is squarely assigned in 40 nodes, and the PAN coordinator is at the center of topology.

$$\text{Throughput} = \frac{\text{Packet\_Lenght} * \text{No\_Successful\_Packets}}{\text{Total\_time}} \tag{4}$$

$$\text{Average delay} = \frac{\text{Total\_packet\_delay}}{\text{No\_successful\_packets}} \tag{5}$$

$$Utilization = \frac{\text{Packet\_Length*No\_Successful\_Packets}}{\text{Total\_time * No\_channel * Data\_Rate}} \tag{6}$$

$$\text{Drop} = \frac{\text{No\_dropped\_packets}}{\text{No\_total\_generated\_packets}} \tag{7}$$

Figure 7 shows the simulation results using the original protocol with two different topologies. Both throughput and utilization grow fast for first seconds but become very steady after 300 seconds as shown in Figures 7 a and b. The steady state is a feature of the original IEEE 802.15.4. The throughput results are similar to the

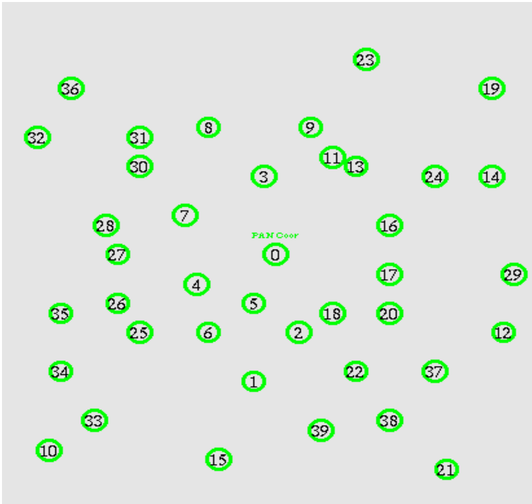


Figure 5. Topology A with 40 random nodes, non-overlapping.

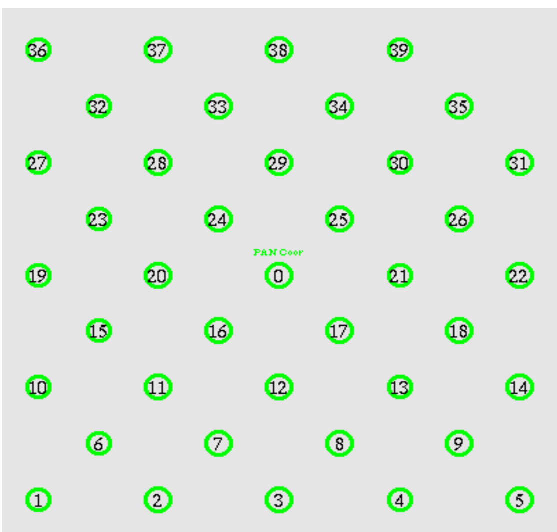


Figure 6. Topology B with 40 squarely assigned nodes, non-overlapping.

utilization results. The results in Figures 7(c) and 7(d) reveal the throughput, utilization, average delay and drop-off of topology B are much better than that of topology A.

Hash mechanisms simulation results

The simulation results for the proposed hash mechanisms are shown in the figures below. Both random and square 40 node topologies are simulated. The results for throughput, utilization, average delay and drop-off are compared with those for the original protocol for two different topologies.

Random method

The proposed mechanism uses a random prime generator to produce the random channel before the channel be assigned. The throughput, utilization, average delay and drop are compared with original protocol dividedly in two different topologies. The simulation results for topology A are illustrated in Figure 8, and for topology B in Figure 9. In Figures 8(a), 8(b), 9(a) and 9(b), the results show that throughput and utilization of random method are the best. The results are much better than pervious hash mechanisms and the curves are similar to double hashing.

In Figures 8(c), 8(d), 9(c) and 9(d), the results of average delay and drop are also better than original protocol. In Figure 8(d) and 9(d), the results show that performances of drop in topology A are better than the topology B and the curves are also similar to double hashing. The results show that random method is an efficient hash mechanism for improving performance of IEEE 802.15.4 duo to it can efficient to avoid hashing collision.

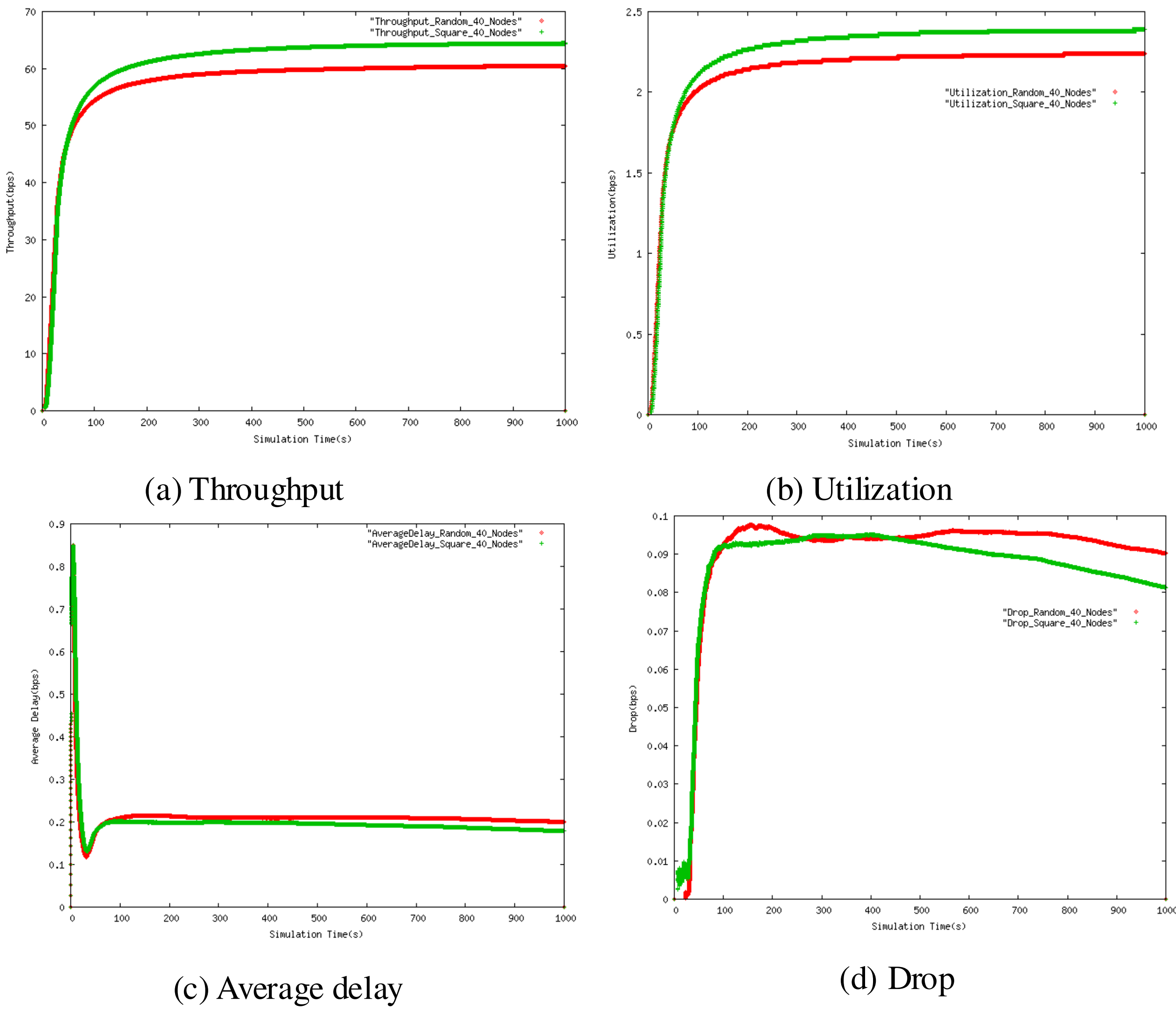
Enhanced linear probing

This mechanism uses a random number generator to find the next available channel. The throughput, utilization, average delay and drop are compared with original protocol dividedly in two different topologies. The simulation results for topology A are illustrated in Figure 10, and for topology B in Figure 11. The results of throughput and utilization of using the enhanced linear probing are increasing highly in Figure 10(a), 10(b), 11(a) and 11(b). In the beginning, the throughput and utilization are lower than original protocol but they are increasing and approaching steady after 100 seconds. Therefore, the throughput and utilization are better than original protocol in two different topologies. In Figure 10(c), 10(d), 11(c) and 11(d), average delay and drop are illustrated in topology A and B. The results show that performances of two measures are better than original protocol. The drawbacks of the four measures are the simulation performances which are lower than that of original protocol in the beginning. Meanwhile, the results are nearly in two different topologies.

Enforcement of completeness of simulation

The locations of node are not sure in the real environment generally. In order to generalize the completeness of the simulated topologies, results of two simulations are used to calculate their average. The results of four average measures of two hash mechanisms are illustrated dividedly in Figures 12, 13 14 and 15.

The results of average throughput and utilization are better than original protocol in Figure 12 and 13. In the beginning, the average throughput and utilization are



(a) Throughput (b) Utilization

(c) Average delay (d) Drop

Figure 7. Performance of the original protocol.

lower than original protocol but they are increasing and approaching steady after 300 seconds. The results of Figure 14 and 15 reveal that the average cases of drop and average delay are lower than original protocol in the beginning. The results show that average performances of two measures are better than original protocol after 200 seconds. The results of simulation reveal that average cases of topology could simulate the real environment more generally. On the other word, their results can represent general situation of any topology.

DISCUSSION

As yet, two proposed hash mechanisms have been simulated and compared with original protocol based on NS-2 simulations. In order to detail the results clearly, the throughput, utilization, average delay and drop of two mechanisms are illustrated and compared with original protocol dividedly in topology A and B as shown in Figure 16, 17, 18 and 19. All of them show the results at the time of 1000 seconds respectively.

The throughput is an important performance of measurement for wireless sensor network. In Figure 16 and 17, the results of simulation show that throughput and utilization of two hash mechanisms are better than the original. However, their curves reveal the throughput and utilization are lower than original in the beginning. In Figure 18 and 19, the results of simulation show that average delay and drop of the random method is better than that of the enhanced linear probing. However, their curves are higher than original protocol in the beginning.

The enhanced linear probing is better than original due to the probing rule is improved and resolves the clus-

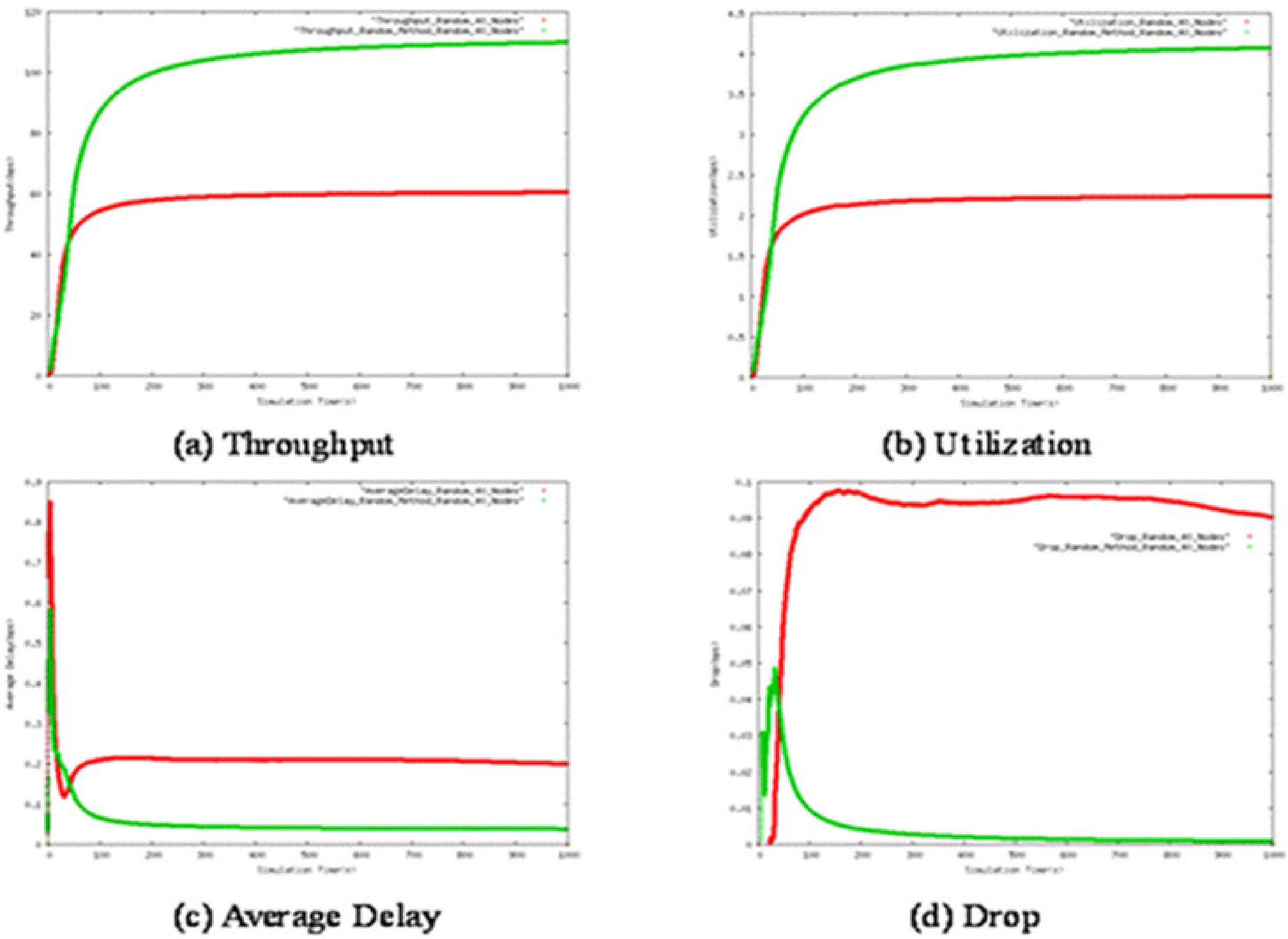


Figure 8. Performance of random method in topology A.

tering problem. The results reveal the random method is the best mechanism than others without respect to use topology A or B because it can efficient to avoid hashing collision. The results of hashing can be different due to the random numbers are not repeated before the key is changed.

Although the results show that throughput, utilization, average delay and drop-off of the rehashing mechanism are better than for the original protocol, however, the drawbacks of the mechanism are that the simulation performance is lower than that of original protocol in the beginning. The reason that rates of channel usage are lower in the beginning when using the hash channel selection mechanism is less efficiency. In this respect the original shows better performance. A channel selection mechanism is proposed for improving the performance of IEEE 802.15.4. When the original protocol performs better than the proposed hash mechanism, then we switch to the original hash mechanism. This hybrid channel selection mechanism is better than the original mechanism and can be used to effectively increase the performance of IEEE 802.15.4.

Conclusion

The proposed hashing mechanism is simulated by NS-2 and the results are compared with those from the original protocol. The throughput is important for measuring the performance of a wireless sensor network. It can be seen that the throughput and utilization of the rehashing mechanism are better than the original. However, the curves reveal that the throughput and utilization rate are lower than original in the beginning.

In addition, the results of the simulation show that average delay and drop-off of the rehashing mechanism are better than the original. However, the curves are higher then the original protocol in the beginning.

Remarks

In this research, the performance of two hash mecha-

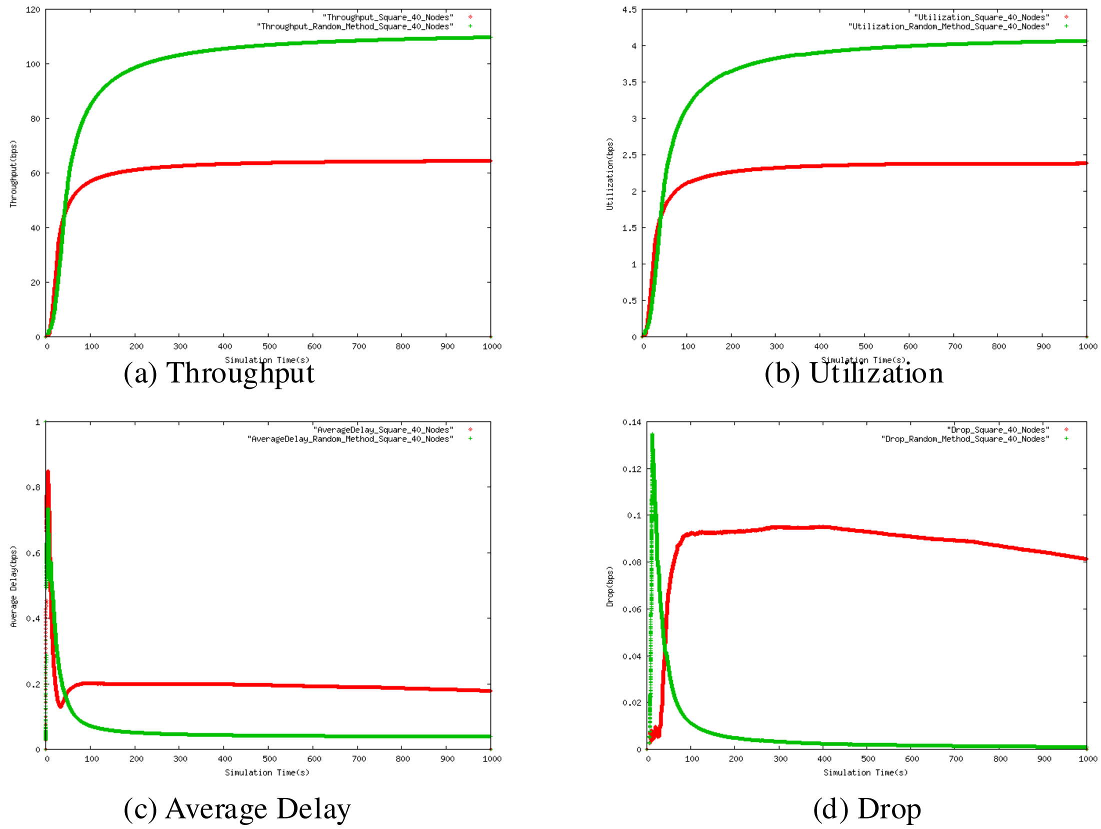


Figure 9. Performance of random method in topology B.

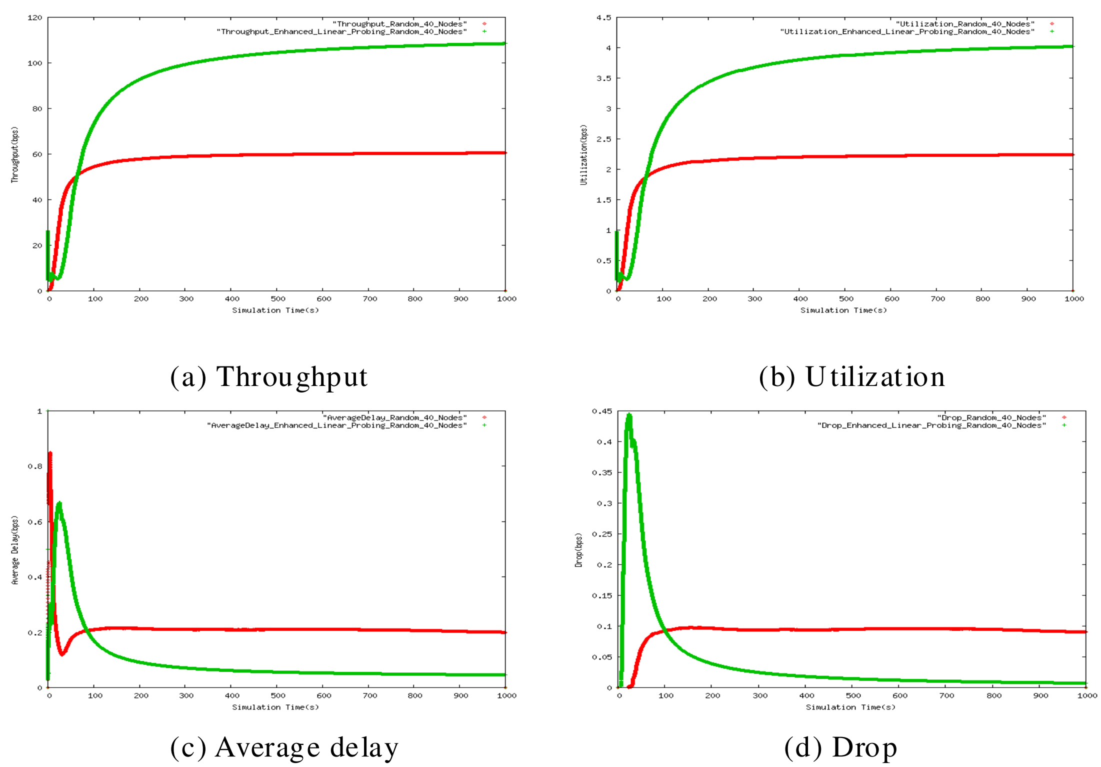


Figure 10: Performance of enhanced linear probing in topology A.

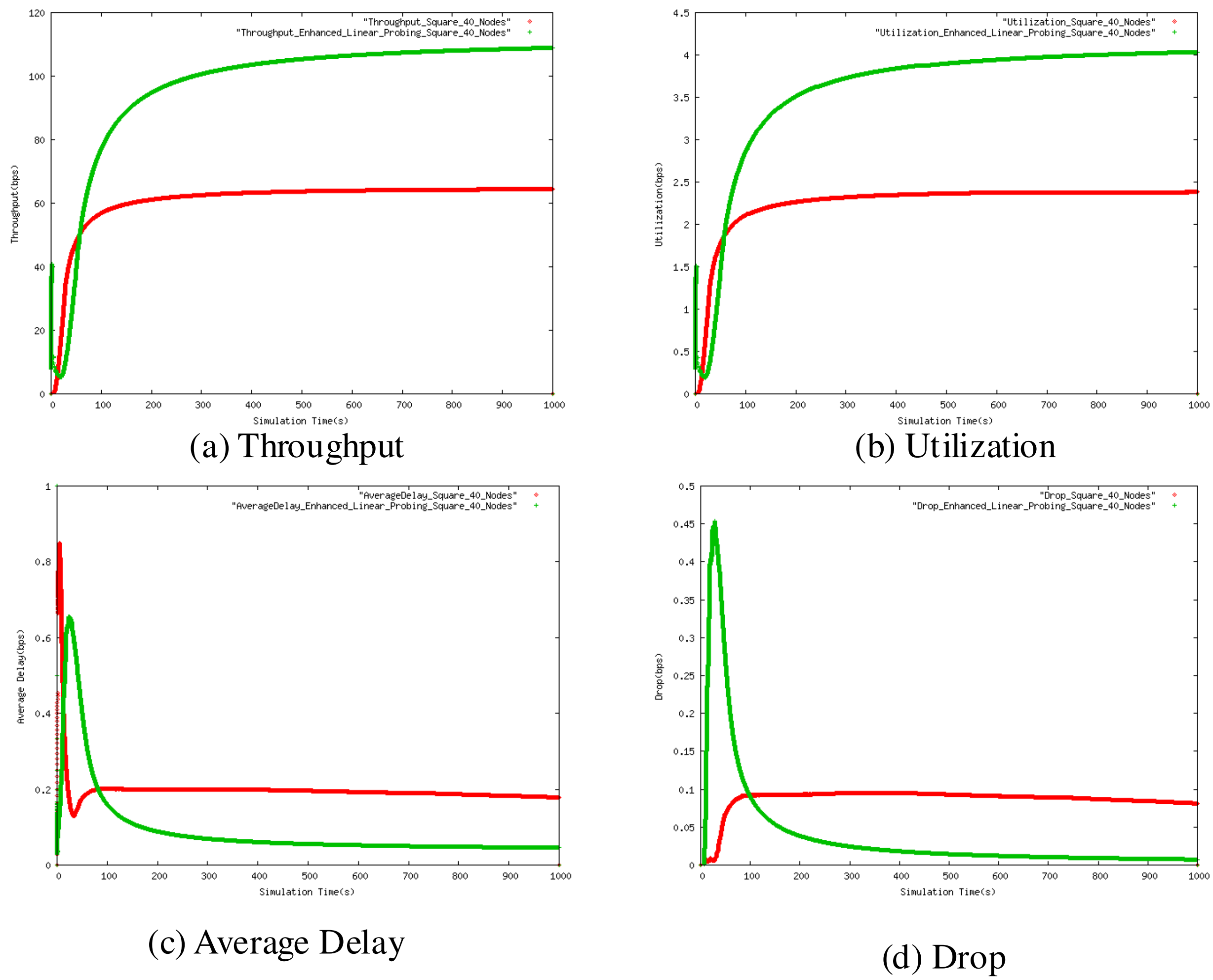


Figure 11. Performance of enhanced linear probing in topology B

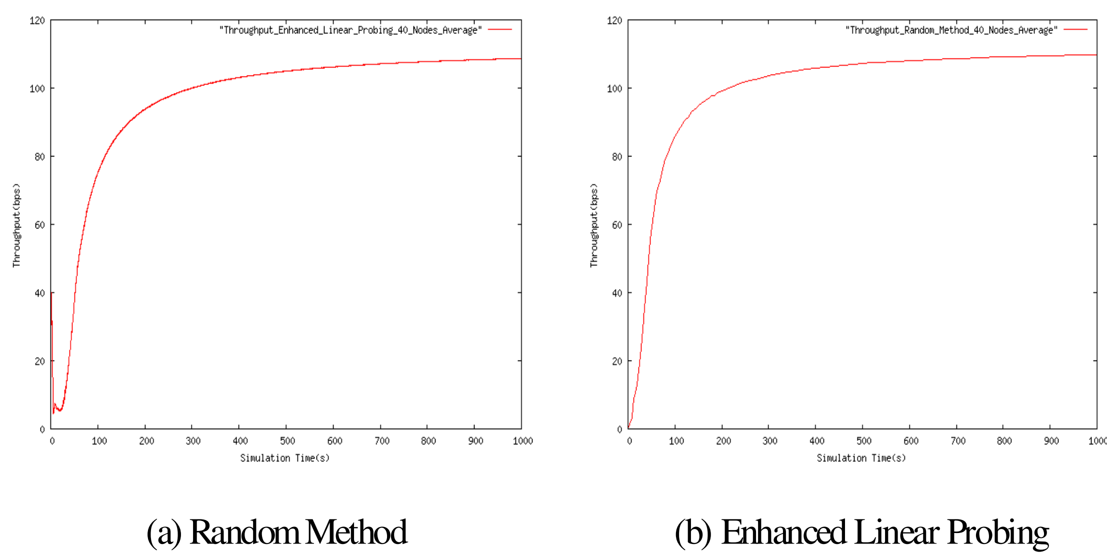
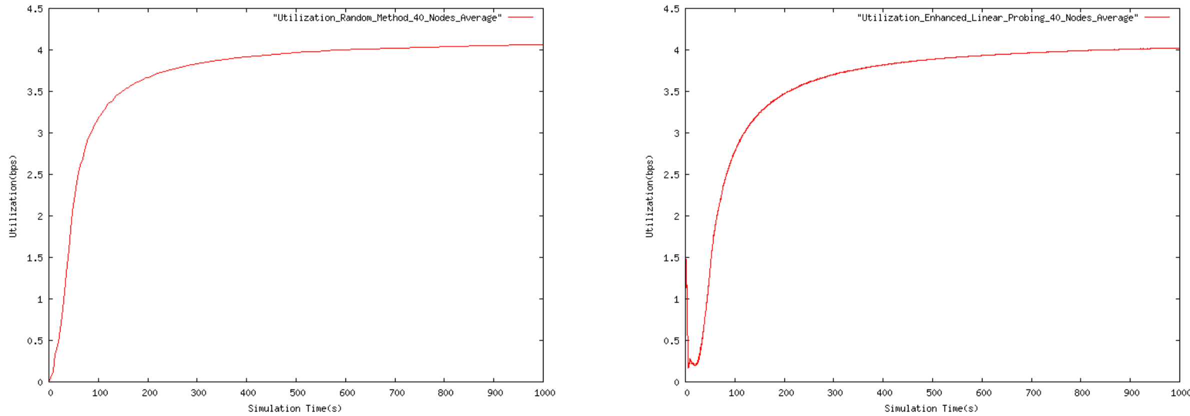
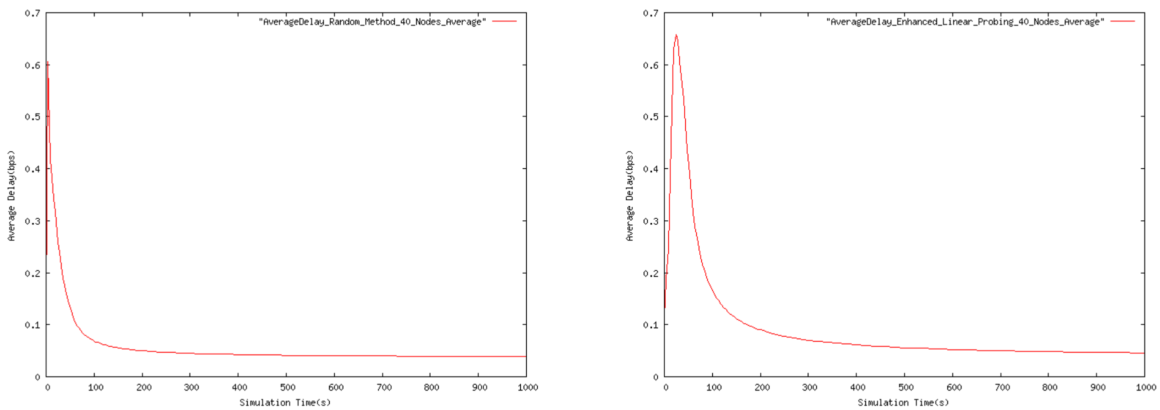


Figure 12. Average throughput of two hash mechanisms in topology A and B.



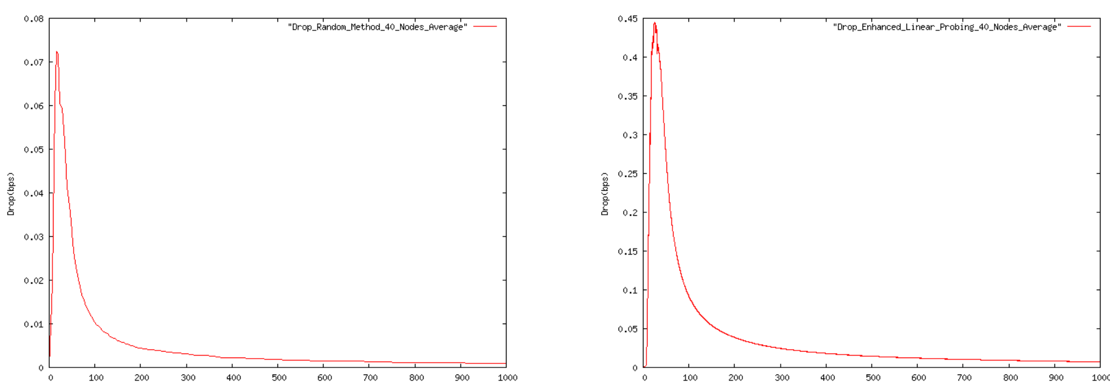
(a) Random Method (b) Enhanced Linear

Figure 13. Average utilization of two hash mechanisms in topology A and B



(a) Random (b) Enhanced Linear

Figure 14. Average of average delay of two hash mechanisms in topology A and B



(a) Random Method (b) Enhanced Linear Probing

Figure 15. Average drop of two hash mechanisms in topology A and B.

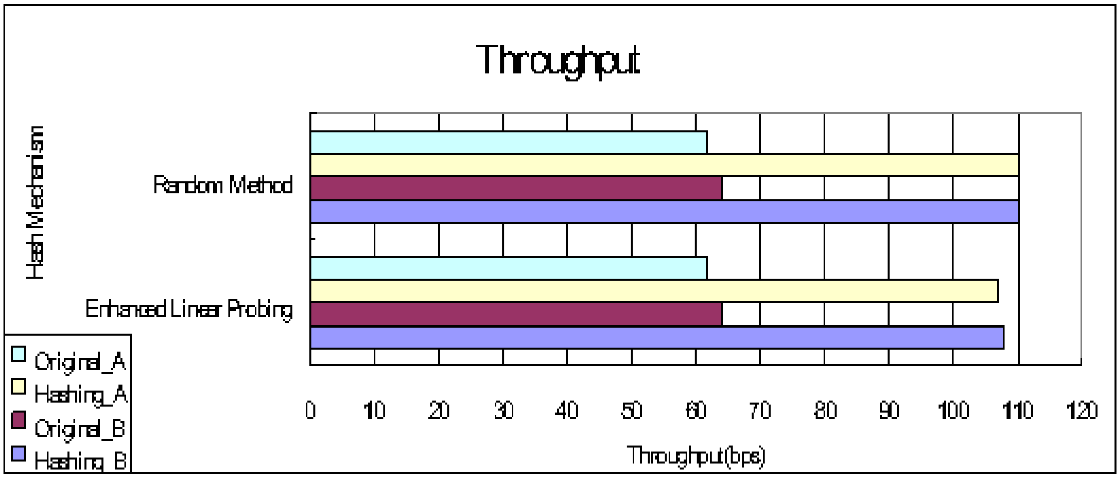


Figure 16. Throughput of two different mechanisms

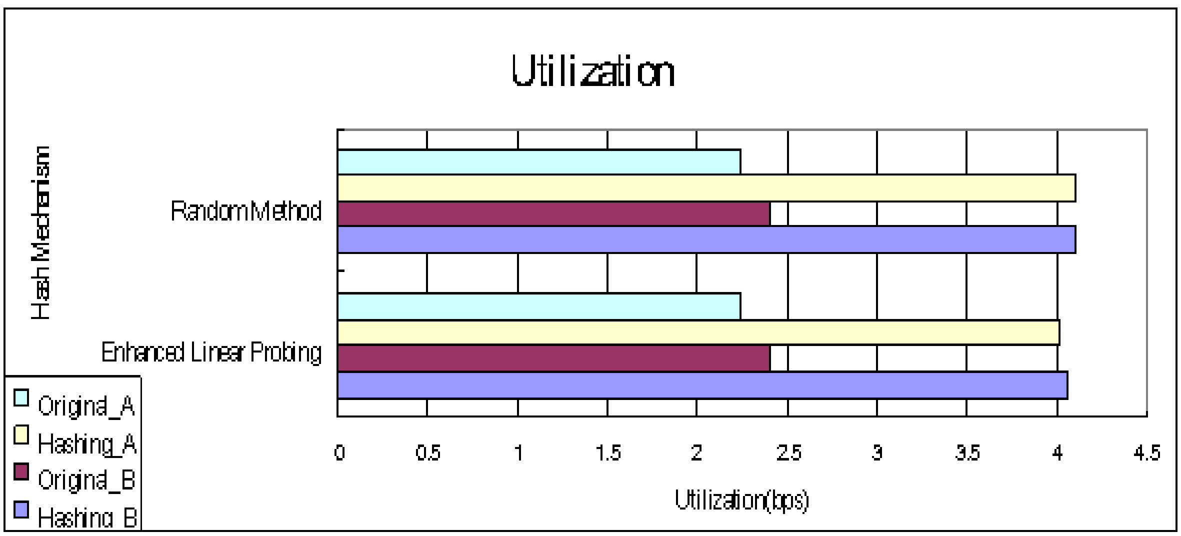


Figure 17. Utilization of two different mechanisms.

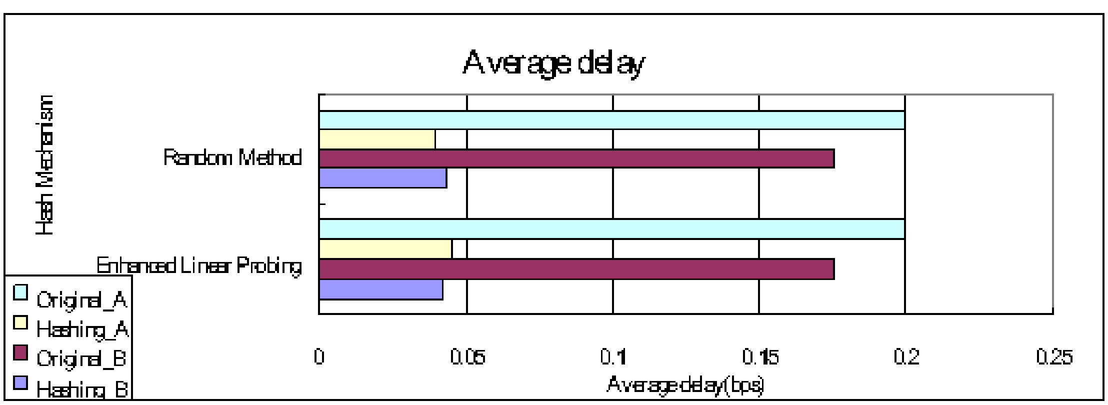


Figure 18. Average delay of two different mechanisms.

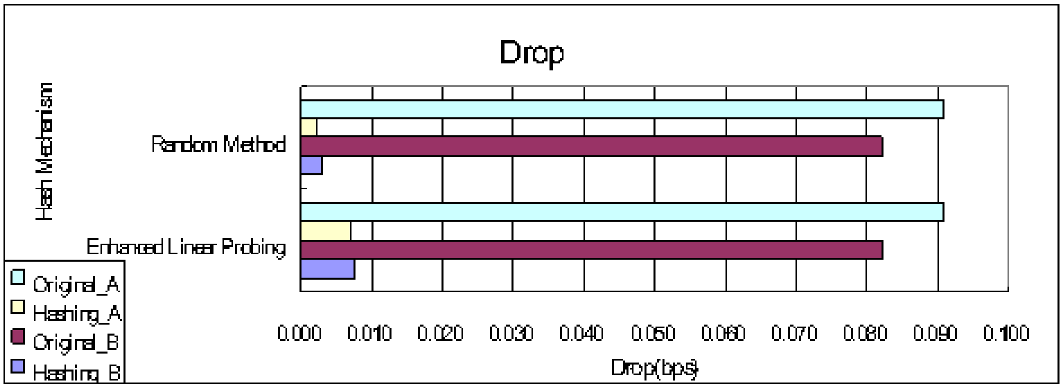


Figure 19. Drop of two different mechanisms.

nisms and original protocol in the IEEE 802.15.4 have been simulated and evaluated based on NS-2 simulators. The results show that throughput, utilization, average delay and drop of two hash mechanisms are improving performance of IEEE 802.15.4 effectively.

The random method is the best hash mechanism among another hash mechanism due to it can increase throughput and utilization, and decrease average delay and drop efficiently. Enhanced linear probing is also out performing original mechanism in improving performance of IEEE 802.15.4.

In order to generalize the completeness of the simulated topologies, average results of two simulations are calculated. A channel selection mechanism is proposed for improving performance of IEEE 802.15.4. This hybrid channel selection mechanism is better than original mechanism and increase performance of IEEE 802.15.4 effectively.

Limitation and future work

In this research, the results show that the two hash mechanisms to improve performance of IEEE 802.15.4 effectively. In addition, while the coordinator at the center of topology; the performances of hash mechanisms are better than the coordinator at other position of topology. Therefore, the reason that coordinator of LR-WPAN has to set at the center of topology generally. However, facing unknown factors or problems in a real Zigbee network environment, practical implementation of these mechanisms are needed. Moreover, the proposed hash mechanism can be adapted for use in the other wireless communication protocols.

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APPENDIX

The pseudo code of the random method mechanism is shown as follows.

```
Random Method
let prime[46] be a 46 primes array between 1 to 200
count ← 1
while(ture)
  if count mod 27 = = 0
    key ← prime[Rand() % 46]
do Current_Channel ← (Current_Channel + key) mod 27
count ← count + 1
return Current_Channel
```

The enhanced linear probing is shown as the following pseudo code.

```
Enhanced_Linear_Probing (Current_Channel)
while Using_Channel_list = = Current_Channel
do Current_Channel ← Rand() % 27
return Current_Channel
```