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# HYBRID ADJUSTMENT DELAY AND SUPERFRAME DURATION SCHEME TO IMPROVE PERFORMANCE IEEE 802.15.4 NETWORKS

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**Abstract**

The network based on IEEE 802.15.4 have several challenges such as how to allocate guaranteed time slot (GTS) properly and how to reduce go to next backoff stage. The coordinator node will allocate GTS size when there is request from node. The node will perform random backoff and then will detect clear channel assessment (CCA). The problem of those as following: first, when there is request from node to allocate GTS size, coordinator node will allocate slot for it, however, if size of slot allocation improperly will cause bandwidth utilization wasted and decrease of goodput, respectively. Second, when there is node detect CCA busy condition, the node will increase number of backoff and entering to next back of stage, however, it will cause more energy consumption. This article proposes a hybrid adjustment delay scheme and superframe duration scheme (H-ADEDUS) to improve performance IEEE 802.15.4. H-ADEDUS has proven can allocate GTS efficiently based on request from device node and adjust delay when detect channel is founded busy. The result of simulation and analytical model show that H-ADEDUS outperform to scheme 1, scheme 2 and scheme 3 in term of probability successful transmission, network goodput, bandwidth utilization and energy consumption, respectively.

Keywords: Energy consumption, Guaranteed time slot, H-ADEDUS.

## 1. Introduction

Wireless sensor networks are networks that comprised of large number of sensors that is implemented for variety applications. One of candidate for application which use for many area applications are IEEE 802.15.4 standard (known as scheme 1). The scheme 1 has designed for sublayer comprised of physical layer (PHY) and medium access control (MAC), respectively. The scheme 1 have several specifications as following: low power consumption, short transmission range and low-rate wireless personal area networks, respectively [1]. The scheme 1 has superframe duration structure. It is comprised of active portion and inactive portion, respectively. The active portion consist of beacon frame, contention access period (CAP) and contention free period (CFP), respectively. While sleep mode that use saving energy for inactive portion. In CAP, in order to access channel all of nodes have to compete using carrier sense multiple access with collision avoidance (CSMA/CA). On the other hands, for CFP, node will use as dedicated slot which need guaranteed time slot (GTS) that is requested to coordinator node to allocate slot.

In CSMA/CA mode, the node will perform random backoff when find clear channel assessment (CCA) detect busy condition. The coordinator node will allocate GTS size when there is request from node. The problem of those as following: first, when there is request from node to allocate GTS size, coordinator node will allocate slot for it, however, if size of slot allocation improperly will cause bandwidth utilization wasted and decrease of goodput, respectively. Second, when there is node detect CCA busy condition, the node will increase number of backoff and enter to next back of stage, however, it will cause more energy consumption.

The challenge will occur when there is request GTS slot from node to coordinator node, if allocation GTS slot from coordinator node to node only based on standard, so that it will cause bandwidth wasted. On the other hands when node detect CCA in busy condition. Those challenge still interest research on wireless sensor networks area, especially to improve performance of IEEE 802.15.4 networks. The study to evaluate of the slotted CSMA/CA of scheme 1 that use all of allocate frequency and analysis as well as compare each other have been proposed by Alvi et al. [2]. However, still not proposed yet a method.

Ashrafuzzaman et al. [3] have presented analysis about node state and channel state model for performance scheme 1 that conduct with modest way but appropriate. In this method, the authors have presented an analysis for CSMA/CA for CAP portion of beacon enable, which consider for saturation mode. However, all of analysis without consider acknowledgement (ACK). The methods that use mathematical analysis based on Markov chain models, which is used to analysis performance of scheme 1 without packet retransmission consideration have been presented by Park et al. [4].

Jing and Aida [5] have presented how to maximize throughput using adaptive backoff mechanism with Markov model. The authors also compare with using ACK and N-ACK. However, analysis without consider about defer transmission. Wang et al. [6] have studied analysis slotted and unslotted on superframe duration in node state. However, more focus on unslotted. In addition, the analysis without consideration about defers transmission and retransmission.

Zhang et al. [7] have presented about optimization for packet size in order to improve throughput and energy consumption. Analysis included about contention, overhead and channel state. However, analysis still not conducted yet all superframe duration. He et al. [8] have studied about uplink and downlink method using ACK and N-ACK in order to improve the networks.

However, all of analysis only consider about two dimension of Markov chain. Xiao et al. [9] have analysed virtual service time using queue modelling for MAC protocol. However, the analysis only for sleep mode portion. The analysis using mathematical model that was implemented on CAP and CFP has been published by Buratti [10]. However, simulation method still not conducted yet for CAP and CFP. Mahmood et al. [11] have studied about non-beacon enable mode for slotted analysis method. They have conducted ACK and N-ACK model. However, analysis method without defers transmission mode. Park et al. [12] have presented about MAC protocol in term of reliable, delay and energy consumption under low traffic area. However, analysis that is given still general for MAC.

Grover et al. [13] have studied transmission data over long distance that using intermediate node. The method only considers about simulation model. However, the analysis model still not performed yet on long distance area. The modification of Markov chain models with consideration packet retransmission but not including defer transmission have been studied by Khanafer et al. [14]. Gao et al. [15] have published about reduce energy consumption on sleeping option that is adapted by radio shutdown. Analysis including impact duty cycle for throughput and energy consumption. Sai Kiran et al. [16] have proposed sensor node model in multi hop scenarios. The method considered delay, and duty cycle. However, the method without presented defer transmission effect. There are several methods that propose about postpone transmission which is analysed by Markov chain model have been published by [17, 18]. Gribaudo et al. [19] have studied about delay performance on sensor networks. The study considered unslotted portion for MAC protocol. The authors have not considered CAP and CFP as series. However, all of them conduct to CSMA/CA normally, which mean they have no new propose for contention mechanism on CAP portion.

The method how to avoid collision between beacons or even between beacon and data packet which mean that is adjusted beacon starting for networks have been proposed by Wu et al. [20]. Sharma et al. [21] have presented improve performance lifetime and Quality of Service (QoS) using two approach that are MAC layer and routing layer, respectively. However, Analysis method still not presented yet on the paper. The method that using combine CSMA and TDMA or hybrid them for WSN have been studied by Deng et al. [22].

Lin et al. [23] have presented about efficiency energy using two hop extension protocol. The performance will be shown on energy consumption and throughput. However, the method only compared with the standard. Rasouli et al. [24] have presented about adaptive mode on beacon enable. The method will adjust the duty cycle. However, analysis method has been not considered. Rasheed et al. [25] have studied about CSMA/CA that is analysed for part energy consumption in networks, however only idle condition. In addition, they have not proposed yet new scheme for idle condition.

Ha et al. [26] have presented how to enhance EB with shift range of BP mechanism in order to decrease of redundant backoff and CCA, respectively. However, probability of delay will increase. Lee at al. [27] have studied about carrier sensing with adding CS for CSMA/CA mechanism. However, when the superframe is not enough to collect data transmission, the authors without consider about postpone transmission. In addition, on Markov chain state of retransmission condition, still not studied yet.

Wang et al. [28] have analysed bandwidth utilization to improve performance networks in contention periods. The method will be guaranteed delay performance. However, the method has been not compared with other method. The improvement of different mechanisms in order to reduce waiting time for successfully transmission have been proposed by Ko et al. [29]. This method can improve BU on superframe duration. However, collision accident cannot be prevented. Mehr et al. [30] have analysed performance based on distribution interarrival time. The authors have done simulation and analysis model. However, only perform for scheme standard.

This article proposes a hybrid adjustment delay scheme and superframe duration scheme (H-ADEDUS) for IEEE 802.15.4 networks. We call it H-ADEDUS method. H-ADEDUS is developed by Lee et al. [31] and Yundra and Lee [32]. Lee et al. [31] focused to allocate GTS properly based on request from the node. The coordinator node will try to allocate precisely GTS size. However, they have done without consider about blind delay backoff and probability will go to next backoff stage, respectively. Yundra and Lee [33] focused how to adjust delay if CCA in busy condition. However, they did not consider about GTS allocation. On the other hands, they only talk about partially system, like GTS allocation and adjustment delay, respectively. H-ADEDUS focuses adjustment size of GTS based on size of packet data when there is request GTS from node and H-ADEDUS also adjustment of delay when CCA detect busy condition. H-ADEDUS is expected allocate GTS size precisely and adjust delay to reduce collision so can improve performance networks in term of network goodput, bandwidth utilization (BU) and energy consumption (E), respectively. The performance of H-ADEDUS will be conducted by star network topology.

## 2. The Method of H-ADEDUS

In this article proposes H-ADEDUS for IEEE 802.15.4 networks. H-ADEDUS aims to allocate GTS size precisely if there is any node request for allocation GTS. GTS will allocate until maximum 7, otherwise will be dropped. Meanwhile, adjustment delay will be conducted when channel is founded busy condition on first CCA and second CCA as well as adding third CCA in order to reduce collision. For more detail about H-ADEDUS can be shown on algorithm of Fig. 1.

H-ADEDUS is expected to allocate GTS size precisely as well as adjust delay if any node detect channel has been occupied condition. The process blind of backoff will be happened if there is node detects channel has been occupied condition. This matter will cause degradation on networks performance such as goodput, BU and E, respectively. The performance of H-ADEDUS will be performed by Castalia simulator to get the probability of successfully transmissions, network goodput, BU and as well as E on networks. Several parameters will be adopted by Lee et al. [31], for more detail about equation can be summarized by Table 1.

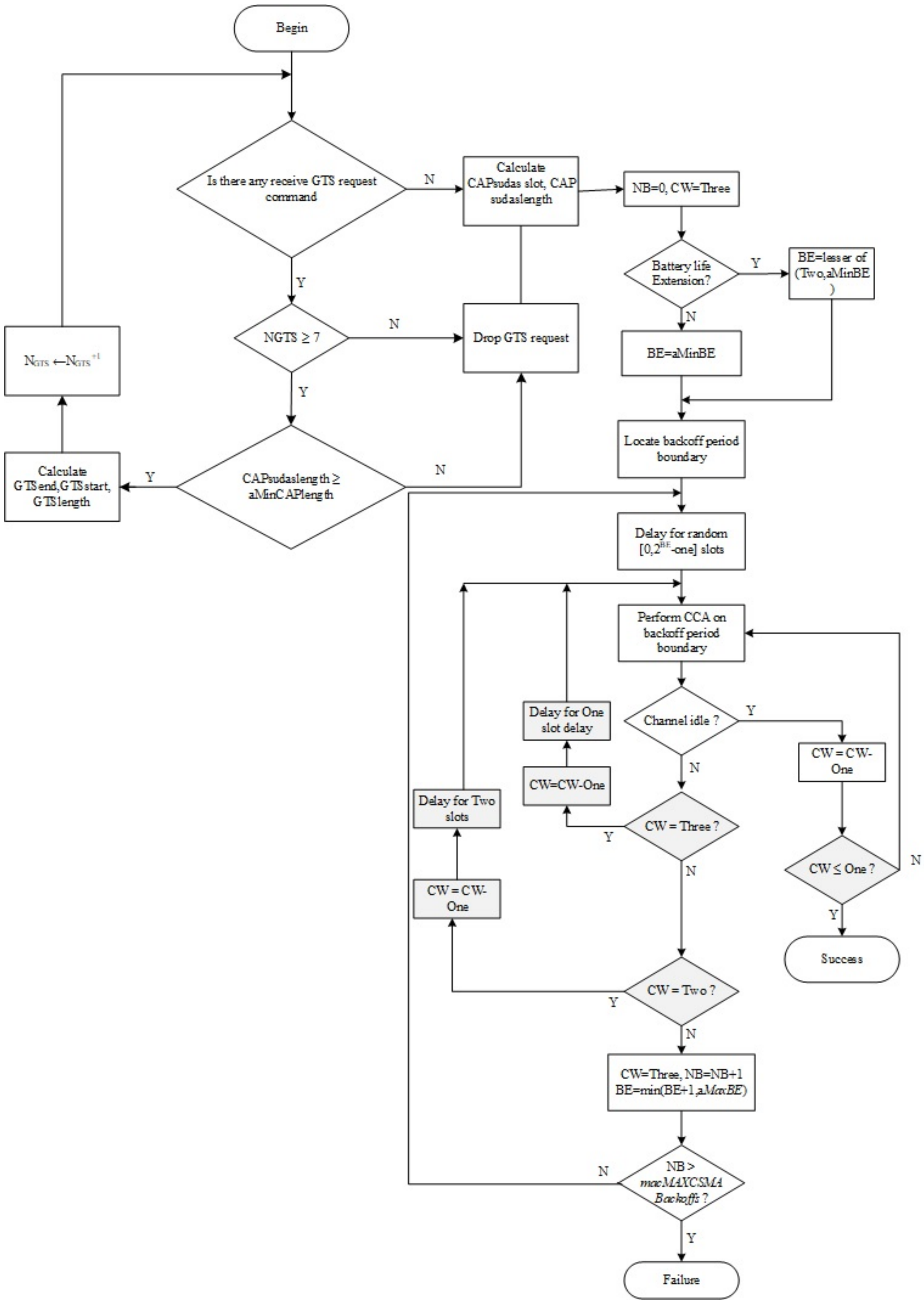


**Fig. 1. Algorithm of H-ADEDUS.**

**Table 1. Equation of CAP and GTS [31].**

| Item | Parameters | Order of Equation |
|---|---|---|
| 1. | $T_{\mathrm{sd}} = \frac{aBaseSuperframeDuration \times 2^{SO}}{\mathrm{Rs}}$ | (1) |
| 2. | $T_{\mathrm{slot}} = \frac{T_{\mathrm{sd}}}{16}$ | (2) |
| 3. | $T_f = T_{\mathrm{data}} + T_{\mathrm{Lack}} + T_{\mathrm{ack}} + T_{\mathrm{LIFS}}$ | (3) |
| 4. | $Tx_n = \frac{\lambda_n \times T_{sd} \times P}{R_b}$ | (4) |
| 5. | $adjslo = \left\lfloor \frac{T_{\mathrm{slot}}}{T_f} \right\rfloor$, *where* $\lfloor x \rfloor$ *is the maximum integer but less than x.* | (5) |
| 6. | $T_{\mathrm{sudas}} = \frac{T_{\mathrm{slot}}}{adjslot}$ | (6) |
| 7. | $\mathrm{N}sudasslot_{\boldsymbol{n}} = \left\lceil \frac{Tx_{\boldsymbol{n}}}{\boldsymbol{T}_{sudas}} \right\rceil$, where $\lceil \boldsymbol{x} \rceil$ is the minimum integer but greater than *x.* | (7) |
| 8. | $GTSstart_n = NumSuperframeSlot \times T_{slot} - T_{sudas} \times \sum_{i=1}^{n} Nsudasslot_i,\ 1 \le n \le N_{GTS}$ | (8) |
| 9. | $GTSlength_n = Nsudasslot_n \times T_{sudas}$ | (9) |
| 10. | $\mathrm{CAP}_{\mathrm{sudasslot}} = NumSuperframeSlot - \left\lceil \sum_{\boldsymbol{n}=\boldsymbol{1}}^{\boldsymbol{N}_{GTS}} \frac{Nsudasslot_{\boldsymbol{n}}}{\boldsymbol{adjslot}} \right\rceil$ | (10) |
| 11. | $CAP_{sudaslength} = NumSuperframeSlot \times T_{slot} - T_{beacon} - T_{sudas} \times \sum_{n=1}^{N_{GTS}} Nsudasslot_n$ | (11) |

In addition, the supeframe duration will be known as SD and the interval time of waiting that is caused by CCA busy condition will be known as $T_{\mathrm{delay}}$, respectively.

$$SD = \frac{\mathrm{aBaseSuperframeDuration\ x\ } 2^{\mathrm{SO}}}{\mathrm{Rs}} \quad \text{[in seconds].} \tag{12}$$

$$T_{delay} = \frac{1 \times Unitbackoffperiod}{Rs} \quad \text{[in seconds].} \tag{13}$$

In this article, all of node in the networks will communicate with coordinator node using CSMA/CA. In order to transmit packet data, each node will perform random delay that value from 0 to ($2^{\mathrm{BE}\ -\ 1}$). If there are node request to GTS allocation, then coordinator will allocate it, if number of GTS lesser than 7 and vice versa coordinator will be dropped GTS request. While there are no GTS request or number of GTS allocation have 7 nodes, then the system going to the random backoff again and then CCA perform. If the channel is founded idle condition so that contention window (CW) will be reduced by 1 (one). H-ADEDUS will make sure that CW lesser or equal one, if CW have fulfilled already, then transmit as soon and vice versa going to looping again. All description of algorithm can be shown on Fig. 1.

Several equations for probability of successful transmission, goodput, BU and E can be adopted by [31, 32] and summarized as Table 2.

**Table 2. Equation of probability successful transmission, goodput, BU and E [31, 32].**

| Item | Parameters | Order of Equations |
|---|---|---|
| 1. | $P_{tsg} = P_{sg} \times \left(\frac{P_{GTS}+1}{P_{sg}}\right) \times (1-d)$ | (14) |
| 2. | $S_{total} = \frac{(N_{WGTSrecvcoord} + N_{GTSrecvcoord}) \times L_{data}}{N_{beacon} \times BI_{coord}}$ | (15) |
| 3. | $BU_{sudastotal} = \frac{BU_{CAPsudaslength} + BU_{CFPsudaslength}}{2}$ | (16) |
| 4. | $P_{succoord} = 1 - P_{dropcoord}$ | (17) |
| 5. | $S_{ades} = \frac{N_{recvcoord} \times L_{data}}{T_{sim}}$ | (18) |
| 6. | $BU_{total} = \frac{(NTq_1 \times TQ_1) + (NTq_2 \times TQ_2)}{N_{beacon} \times CAP_{ades}}$ | (19) |
| 7. | $E_{total} = E_{dev} + E_{Coord}$ | (20) |

Basically, modification of SUDAS and ADES can be obtained flowchart of the H-ADEDUS algorithm as shown in Fig. 1. First of all, the coordinator send beacon in the network, and all of devices receive beacon information. Each node that GTS allocation will try to request to coordinator. Coordinator will check number of GTS allocation, if number of GTS lesser than 7 so will going to calculate length of CAP and GTSstart as well as GTSlength, after that will allocate GTS. On the other hands, if number of GTS more than 7, GTS request will be dropped. Second, set number of CW to 3 slots in order to face CCA 1 and CCA 2 detection. If CCA detect channel condition idle condition and then will check number of CW. If CW reduced one equal or lesser than 1, then immediately packet transmission. Vice versa, will go to perform CCA again.

## 3. Simulation and Results

The performance of H-ADEDUS will be evaluated using experiment simulation. Extended Castalia simulator will be used to run simulation. The performance of H-ADEDUS will be compared with scheme 1 [1], scheme 2 [31] and scheme 3 [32] which comprised of simulation and analysis, respectively. In this research using star topology that comprised of 1 node as coordinator and 20 nodes as client. Distance from coordinator to each node is 10 meters. All of the networks perform using traffic load from 0.1 to 1 in order to compute probability successful transmission, goodput, BU and E, respectively. For more detail parameters can be summarized by Table 3.

The probability of successful data transmission from node to coordinator networks with analytical and simulation can be shown on Fig. 2, respectively. H-

ADEDUS can allocate GTS properly, then CAP of H-ADEDUS longer than other schemes. In addition, H-ADEDUS also can adjust delay effectively when CCA find channel condition has been occupied in order to avoid collision, so that H-ADEDUS has higher probability of successful transmissions than those of scheme 1, scheme 2 and scheme 3 that comprised of analytical and simulation, respectively. Probability of successful transmissions of H-ADEDUS outperform 6.57%, 4.7% and 3.2% of scheme 1, scheme 2 and scheme 3, respectively.

**Table 3. The simulation parameters.**

| Parameter | Value |
|---|---|
| *NumbSupSlots* | 16 (integer) |
| *UBP* | 80 bits |
| $L_{data}$ | 720 bits |
| *PDR* | 250 kbps |
| $P_{transmitter}$ | 31.32mW |
| $P_{receiver}$ | 35.28mW |
| $P_{idle}$ | 712µW |
| *D* | 10 m |
| MAC-Packet-Overhead | 112 bits |
| Length of ACK ($L_{ack}$) | 88 bits |
| Beacon order | 6 (integer) |
| Superframe order | 6 (integer) |
| Backoff $\text{Exponent}_{min}$ | 3 (integer) |
| Backoff $\text{Exponent}_{max}$ | 5 (integer) |

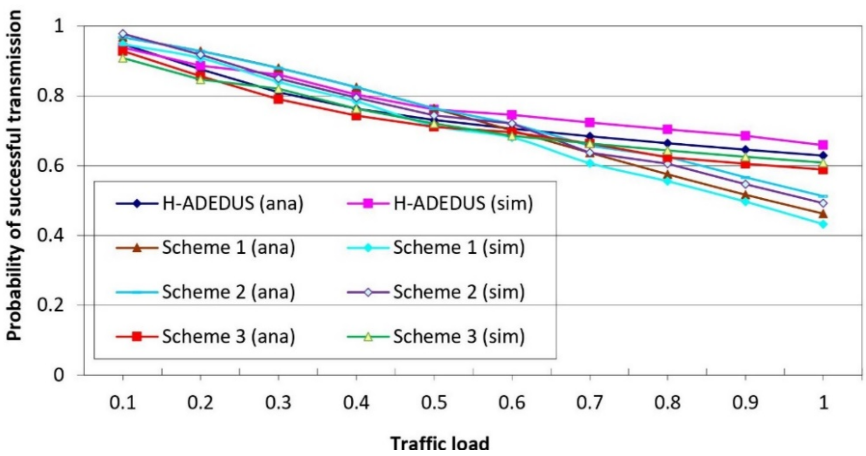


**Fig. 2. Probability of successful transmission.**

Figure 3 shows performance of the network goodput to traffic load. In this case, data of simulation that is obtained very close with analysis result. Network goodput of H-ADEDUS from traffic load 0.1 to 0.6 almost the same with scheme 1, scheme 2 and scheme 3, respectively. However, on heavy traffic H-

ADEDUS outperform to the other schemes, which traffic load increase from 0.6 to 1. The network goodput of H-ADEDUS outperform 7.35%, 4.66% and 4.29% of scheme 1, scheme 2 and scheme 3, respectively. It has proven network goodput of H-ADEDUS higher than the other schemes.

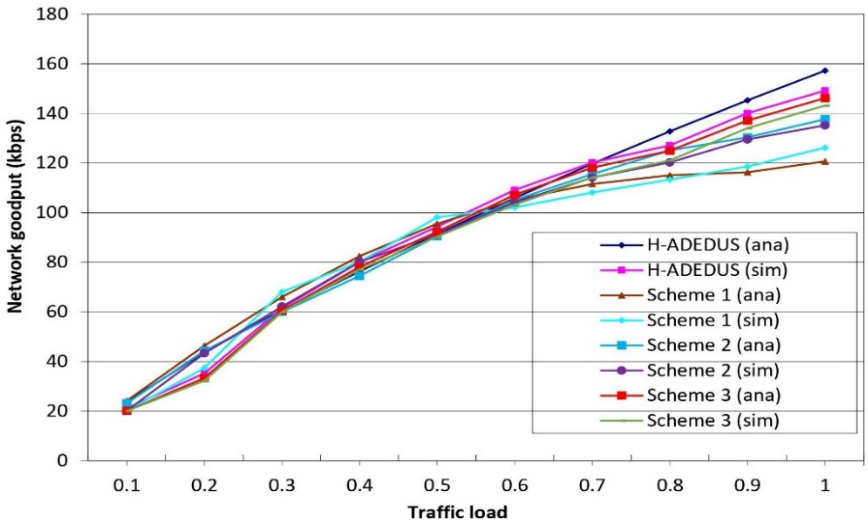


**Fig. 3. Network goodput.**

Figure 4 shows performance of BU to traffic load. The H-ADEDUS method can allocates GTS size properly, which coordinator will allocate in accordance with requested by node, so that BU of H-ADEDUS has better efficiency than the other schemes. Furthermore, H-ADEDUS also adjust delay backoff when find the CCA busy condition. The BU of H-ADEDUS outperform 5.81%, 3.51% and 2.74% of scheme 1, scheme 2 and scheme 3, respectively.

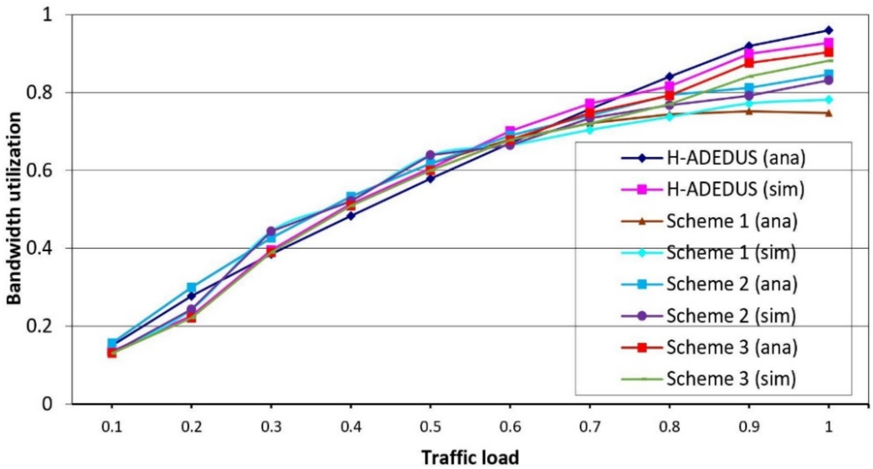


**Fig. 4. Bandwidth utilization.**

Figure 5 shows performance of E to traffic load. H-ADEDUS can adjust delay when CCA perform network and detect channel is not idle, which mean can reduce probability of collision each node in the network. In addition, H-ADEDUS not only has greater probability successful transmission but also has lower retransmission packet data, so that energy consumption of H-ADEDUS lower than the other schemes. The energy consumption of H-ADEDUS decreased by 9.9%, 24.72%, and 29.48% compared to scheme 3, scheme 2, and scheme 1, respectively. It is obviously that H-ADEDUS outperform to the other schemes.

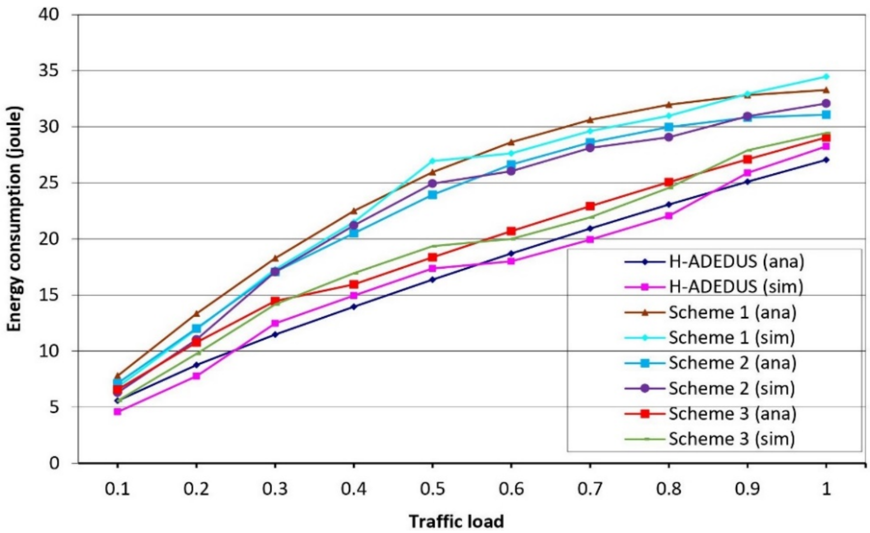


**Fig. 5. Network energy consumption.**

## 4. Conclusions

In this article, H-ADEDUS is proposed to allocate GTS size properly when there is any request from device node and adjust delay when CCA find busy condition. H-ADEDUS has proven can allocate GTS as efficiency based on request from device node and adjust delay on network when detect channel is founded. In this case, can reduce collision accident, so that can improve performance of IEEE 802.15.4 networks. The result of simulation and analytical model show that H-ADEDUS outperform to scheme 1, scheme 2 and scheme 3, respectively. Finally, we can conclude that performance of H-ADEDUS outperform to the other schemes in term of probability successful transmission, network goodput, BU and E, respectively.

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**Nomenclatures**

| | |
|---|---|
| *Adjslot* | The adjustment for the $T_{slot}$ that used integer type |
| $E_{total}$ | Total energy consumption in network |
| $GTS_{length}$ | The length of a GTS allocation |
| $GTS_{start}$ | Starting time of GTS |

| | |
|---|---|
| $N_{sudasslot}$ | The number of request slots for each GTS of SUDAS |
| $Pi_{dle}$ | Power idle |
| *Preceiver* | Power receiver |
| $P_{succoord}$ | Probabilities successful transmission |
| *Ptransmitter* | Power transmitter |
| $P_{tsg}$ | The probability of the successful GTS transmission |
| *Scheme 1* | The IEEE 802.15.4 standard |
| *Scheme 2* | SUDAS scheme |
| *Scheme 3* | ADES scheme |
| $S_{total}$ | The total goodput in the network |
| $T_f$ | The size of time for one data packet transmission and receive ACK packet |
| $T_{sd}$ | The time of Superframe duration |
| $T_{slot}$ | The size of one slot in time duration |
| $T_{sudas}$ | The new time of SUDAS for one slot duration |
| $TX_n$ | The size of time for data packet transmission according to its arrival rate by device n |
| **Abbreviations** | |
| ACK | Acknowledgement |
| ADES | Adjustment Delay Scheme |
| BE | Backoff Exponent |
| BO | Beacon Order |
| BU | Bandwidth Utilization |
| CAP | Contention Access Period |
| CCA | Clear Channel Assessment |
| CFP | Contention Free Period |
| CW | Contention Window |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance |
| D | Distance Coordinator to Node |
| E | Energy consumption |
| GTS | Guaranteed Time Slot |
| H-ADEDUS | Hybrid adjustment delay and superframe duration scheme |
| $L_{data}$ | Length of packet |
| LR-WPAN | Low-Rate Wireless Personal Area Network |
| MAC | Medium-Access-Control |
| N-ACK | Negative-Acknowledgement |
| PDR | Physical data rate |
| PHY | Physical layer |
| SD | Superframe Duration |
| SO | Superframe Order |
| SUDAS | Superframe Duration Adjustment Scheme |
| UBP | Unit Backoff Period |

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