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Performance of Non-Uniform Duty-Cycled ContikiMAC in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Network (WSN) is a promising technology in Internet of Things (IoTs) because it can be implemented in many applications. However, a main drawback of WSN is it has limited energy because each sensor node is powered using batteries. Therefore, duty-cycle mechanisms are introduced to reduce power consumption of the sensor nodes by ensuring the sensor nodes in the sleep mode almost of the time in order to prolong the network lifetime. One of the de-facto standard of duty-cycle mechanism in WSN is ContikiMAC, which is the default duty-cycle mechanism in Contiki OS. ContikiMAC ensures nodes can participate in network communication yet keep it in sleep mode for roughly 99\% of the time. However, it is found that the ContikiMAC does not perform well in dynamic network conditions. In a bursty network, ContikiMAC provides a poor performance in term of packet delivery ratio, which is caused by congestion. One possible solution is ContikiMAC should increase its duty-cycle rate in order to support the bursty traffic. This solution creates a non-uniform duty-cycle rates among the sensor nodes in the network. This work aims to investigate the effect of non-uniform duty-cycle rates on the performance on ContikiMAC. Cooja simulator is selected as the simulation tool. Three different simulation scenarios are considered depending on the Clear Channel Assessment Rate (CCR) configurations: a low uniform CCR value (Low-CCR), a high uniform CCR value (High-CCR) and non-uniform CCR values (Non-uniform-CCR). The simulation results show that the Low-CCR scenario provides the worst performance of PDR. On the other hand, the High-CCR scenario provides the best performance of PDR. The Non-uniform-CCR provides PDR in between of Low-CCR and High-CCR.

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1. INTRODUCTION

WSN has been widely explored and becoming one of the most important technology for IoTs. WSN has a wide range of applications such as military applications, health care applications, environmental monitoring, industrial process control, home intelligence, security and surveillance [1].

WSN consists of small devices called sensor nodes that can be deployed to collect information about the environment conditions such as temperature, humidity, harmful chemical, light intensity and etc. These sensor nodes are self-configured that cooperate among them to establish an ad-hoc network in order to deliver the sensing data from each sensor node to the base station, which usually connected to the internet. A main problem of WSN is limited energy, where the sensor nodes powered using batteries. Because of this, duty-cycle mechanisms are introduced to reduce energy consumption of the sensor by making it to be almost of the time in sleep mode but still can be participate in the communication.

Among well-known duty-cycle mechanisms are B-MAC [2], X-MAC [3], BoX-MAC [4], WiseMAC [5] and Contiki-MAC [6]. In ContikiMAC, nodes sleep most of the time and periodically wake up to check for any radio activity. If a packet transmission is detected, the receiver stays awake to receive the next packet and sends a link-layer acknowledgement. To send a packet, the sender repeatedly sends the same packet until a link-layer acknowledgement is received. Broadcast packets do not result in link-layer acknowledgements. Instead, the sender repeatedly sends the packet during the full wake-up interval to ensure that all neighbours have received it.

Based on the previous studies, it is found that ContikiMAC provides a poor performance in dynamic conditions of WSN. When a low duty-cycle rate is used, high possibility of congestion might happen at the sensor nodes due to the high incoming packets, which will reduce the performance of the WSN in term of packet delivery ratio but the energy consumption will remain low. Otherwise, when a high duty-cycle rate is used, the packet delivery ratio performance is improved but with an increase of the energy consumption. Because of this, ContikiMAC should dynamically changes its duty-cycle depending on the networks condition. Sensor nodes should used high duty-cycle when incoming packets detected to achieve better packet delivery ratio. On the other hand, sensor nodes should use low duty-cycle when no packet detected to reduce energy consumption. This create non-uniform duty cycle rates among the sensor nodes in the network. Because of this, it is very important to study the effect of non-uniform duty-cycle rates on the performance of WSN.

2. RELATED WORKS

ContikiMAC has been intensively evaluated and taken by many researchers in the WSN community as the performance comparison of their proposed duty-cycle mechanisms. For example, V. Michopoulos et al. [7] evaluated performance of ContikiMAC in congestion conditions. Based on this evaluation, they came out with a new duty cycle-aware congestion control mechanism called DCC6 that achieves a higher goodput and a lower packet loss than the previous works. Moreover, DCCC6 maintains low energy consumption, average time delay and a high degree of fairness.

M. Michel et al. [8] performed a details analysis on the performance of ContikiMAC on the efficiency of its transmission procedure that relies on sending full data frames. The study includes a comparison between ContikiMAC, X-MAC and enhanced version of X-MAC. The study reveals that the better efficiency of ContikiMAC can be attributed to two specific mechanisms: the fast sleep optimization that shortens the wake-up period and more efficient transmission procedure. The combination of these mechanisms helps ContikiMAC to achieve a better packet delivery ratio than X-MAC together with a reduced latency and a drastically lower energy consumption.

JG Ko et al. [9] explored the interoperability performance of ContikiMAC and TinyOS LPL, which are the default low-power MAC protocols in Contiki and TinyOS respectively. The study shows that various parameters at the two low-power MAC protocol implementations can be configured so that they can communicate well. On the other hand, the results show that when poorly configured, the interoperating performance can severely suffer.

A King et al. [10] estimated the network lifetime of ContikiMAC in a very busy radio environment. They found that the network lifetime of ContikiMAC can be up to 11 times shorter than in a quiet environment. Radio interference triggers the receive mechanism causing an unnecessary wake-up which leads to an increase in a node’s energy consumption.

MF Youssef et al. [11] provided an analysis on the impact of spatial CCR configuration on the performance of ContikiMAC. Sensor nodes in the network are assigned with different CCR according to their distance fro the sink. Sensor nodes located near to the sink is set with a higher CCR value. Otherwise, sensor nodes located further away from the sink is set with lower CCR value, which reduce the nodes activity. Two different patterns of CCR configuration are considered: diagonal and rectangular. In the diagonal configuration, sensor nodes in the same diagonal location having the same CCR value. In the rectangular setup, sensor nodes located to the furthest square sides against the sink are assigned the same CCR values. For other sensor nodes, the CCR values are to be increased till reach the sink.

However, MF Youssef et al. focuses on the strategy of CCR assignment and only consider pre-determined grid topology configuration in their works. In this paper, we evaluate the performance of ContikiMAC using non-uniform CCR values with a random pattern of CCR configuration. The results could helps other in designing a dynamic duty-cycle mechanism.

3. CONTIKIMAC PROTOCOL ARCHITECTURE

ContikiMAC [6] is a sender initiated and asynchronous duty-cycle mechanism. ContikiMAC ensures that nodes sleep most of the time but can still participate in the network communication, which reduce the energy consumption of the nodes significantly. In order to achieve it, ContikiMAC uses a power efficient wake-up mechanism, which require precise timing through a set of timing constraints. Other than that, ContikiMAC implements a fast sleep optimization that allow sensor nodes go to sleep quickly after detected false-positive CCA wake-ups and a transmission phase-lock optimization to reduce the transmission by learning the wake-up phase of the receiver.

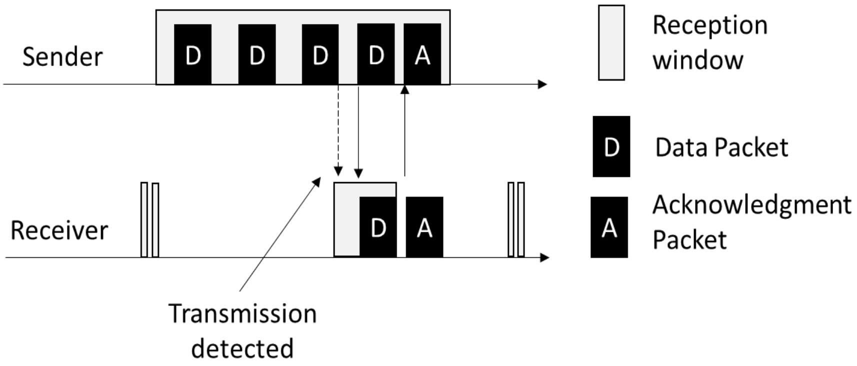

Figure 1. Unicast transmission in ContikiMAC

ContikiMAC provides two types of transmission which are unicast and broadcast. In unicast transmission, if a packet transmission is detected during a wake-up, the receiver remains active to be able to receive the packet. After the whole packet has been received, the receiver sends a link layer acknowledgement to the sender. Once the sender has received the link layer acknowledgment packet, the sender sends the consecutive packets to the receiver within the full wake-up interval. The principle operation of ContikiMAC in unicast transmission is shown in Figure 1 [6]. In a broadcast transmission, the sender repeatedly sends the broadcast packet during the full interval of the wake-ups in order for all neighbours receive the packet. There is no link-layer acknowledgement that is sent by the receiver after receiving the packet. The priciple operation of ContikiMAC in broadcast transmission as shown in Figure 2 [6].

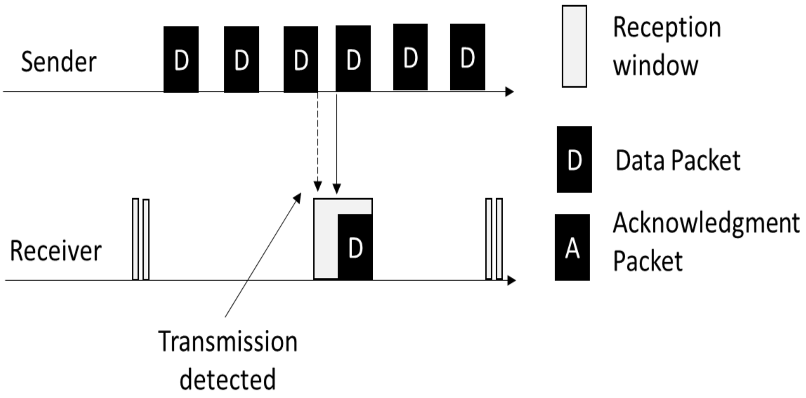

Figure 2. Broadcast transmission in ContikiMAC

ContikiMAC uses a very short interval of Clear Channel Assessment (CCA) mechanism to check for any activity on the channel, which is indicated using Received Signal Strentgh Indicator (RSSI) of the radio transceiver. If the RSSI is below a given threshold, indicating that the channel is clear and the CCA returns positive. If the RSSI is above the threshold, indicating that the channel is in use and the CCA returns negative. Figure 3 shows the ContikiMAC's timing requirement [6]. The timing requirements as the following:

t_s: the interval between each packet transmission.
t_r: the time required for a stable RSSI, needed for a stable CCA indication.
t_c: the interval between each CCA.
t_a: the time between receiving a packet and sending the acknowledgment packet.
t_d: the time required for successfully detecting an acknowledgment from the receiver.

Two rules must be satisfied for ContikiMAC to work properly. The first rule is the interval between each packet transmission, t_i must be smaller than t_c to ensure either the first or the second CCA is able to see the packet packet transmission. If t_c would be smaller than t_i, two CCAs would not be able to reliably detect a transmission. The second rule is the requirement on the shortest packet size that ContikiMAC can support. For two CCAs to be able to detect a packet, the packet transmission cannot be too short that it falls between the CCAs. Specifically, t_s, the transmission time of the shortest packet, must be larger than $t_r + t_c + t_r$.

In the phase-lock optimisation, the sender learns a receiver wake-up phase to optimise its transmissions. It is done by taking the time at which the sender receive the link-layer acknowledgement from the receiver. The reception of the link-layer acknowledgement means the sender has successfully transmitted a packet within the receiver's wake-up window. This information is used by the sender to learn the receiver's wake-up phase. After the sender has learned the wake-up phase of the receiver, the sender can initiate the future transmission to this receiver just before the receiver is expected to be awake, which will reduce number of repeatative transmissions.

When there is no traffic, the duty-cycle ratio of ContikiMAC is mainly contributed by the CCA. This mean, it is considered a waste of energy if a high CCR is used when compared to a low CCR. However, when there is traffics, a high CCR is needed very to deliver packets efficiently to the base station. Using a low CCR increase the possibility of congestion to happen that reduce the packet delivery ratio. Because of this, it is very important for the CCR to be changed dynamically based on the condition of the network that causes a non-uniform distribution of CCR values among sensor nodes in the network. This work will study the effect of using non-uniform CCR values on the performance of ContikiMAC.

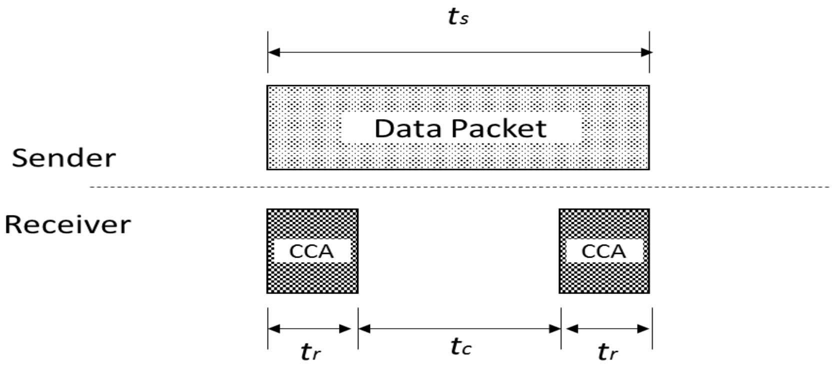

Figure 3. ContikiMAC timing requirement

4. SIMULATION CONFIGURATION

In this study, Cooja simulator is selected as the simulation tool. Cooja is a simulator for Contiki OS. Three simulation scenarios are defined: a low uniform CCR (Low-CCR), a high uniform CCR (High-CCR) and non-unifrom CCR (Non-uniform-CCR). In the Low-CCR scenario, sensor nodes are set to have a low CCR value that is equal to 4 Hz. For High-CCR scenario, the sensor nodes are set to a high CCR value which is 32 Hz. The Non-uniform-CCR scenario is set to have non-uniform values of CCR: 4 Hz, 8 Hz, 16 Hz and 32 Hz. The measured performance metrics are Packet Delivery Ratio (PDR), power consumption and percentage of duty-cycle.

A random topology network is established in the simulation as shown in Figure 4. The network consists of 25 sensor nodes distributed in about 1 km^2 area. Node 1 is chosen as the sink node. Sky mote [12] is selected as the sensor mote model. The transmission range is set to the maximum, which is 125 m as in the datasheet. Unit Disc Graph Medium (UDGM) [13] is selected as the radio model. The network is simulated in four different packet rates: 1/15, 1/10, 1/5, 1 and 5 packets/s. Summary of the simulation configurations are shown in Table 1.

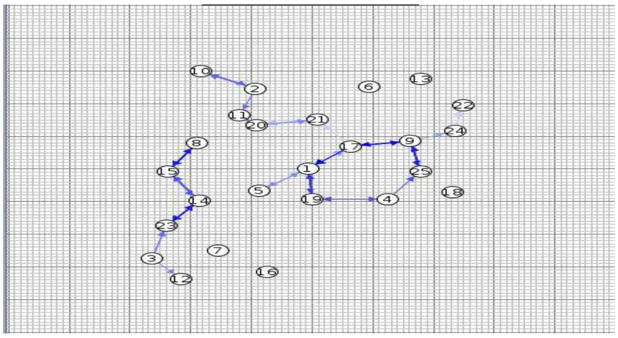

Figure 4. Random Network Topology

Table 1. Simulation Configurations

No.	Parameters	Settings
1	Radio duty cycle	ContikiMAC
2	Clear Channel Assessment (CCA) rate	Low-CCR scenario All nodes are set to have CCR = 4 Hz High-CCR scenario All nodes are set to have CCR = 32 Hz Non-uniform-CCR scenario node 2-7 are set to have CCR = 4 Hz node 8-13 are set to have CCR = 8 Hz node 14-19 are set to have CCR = 16 Hz node 20-25 are set to have CCR = 32 Hz
3	Packet rates	1/15, 1/10, 1/5, 1 and 5 packets/s
4	Sensor mote type	Sky mote
5	Radio model	Unit Disk Graph Medium (UDGM)
6	Transmission range	125m
7	Area	1km^2

5. RESULTS AND ANALYSIS

Figure 5 shows the average PDR over different packet rates for all scenarios. The results shows that PDR is decreased with the increase of packet rates for all the scenarios. The Low-CCR scenario gives the lowest PDR performance among the three scenarios. This is because Low-CCR scenario uses the lowest uniform CCR value, which is the largest interval between two CCA's when compared with other scenarios. The sender require a significant delay to successfully deliver a packet to the receiver that can lead to congestion. On the other hand, the High-CCR scenario uses the highest uniform CCR value achieves the highest PDR. The Non-uniform-CCR provides PDR in between of Low-CCR and High-CCR scenarios.

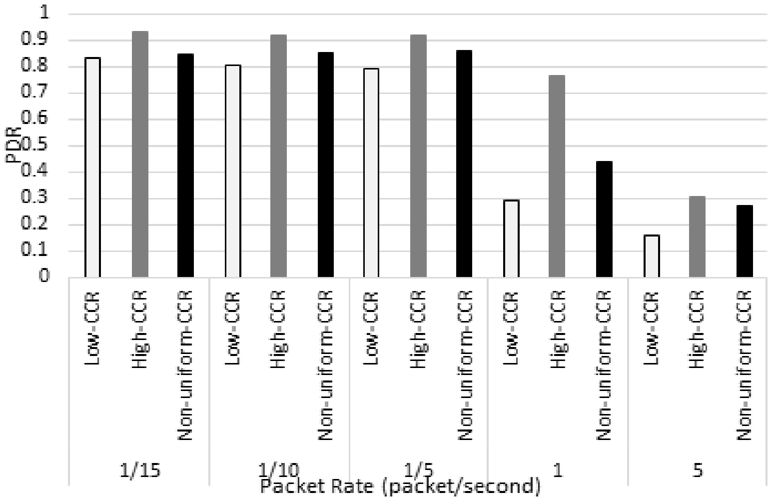

Figure 5. Average PDR over packet rates

Figure 6 shows the average power consumption over packet rates for all scenarios. Based on the graph, the Low-CCR scenario provides the lowest power consumption when compared to other scenarios. By having the lowest CCR value, the nodes assess the channel at the least frequent when compared to the other scenarios. On the other hand, High-CCR scenario provides the highest power consumption because nodes are most frequent assessing the channel. The Non-uniform-CCR scenario provides a performance in between Low-CCR and High-CCR scenarios.

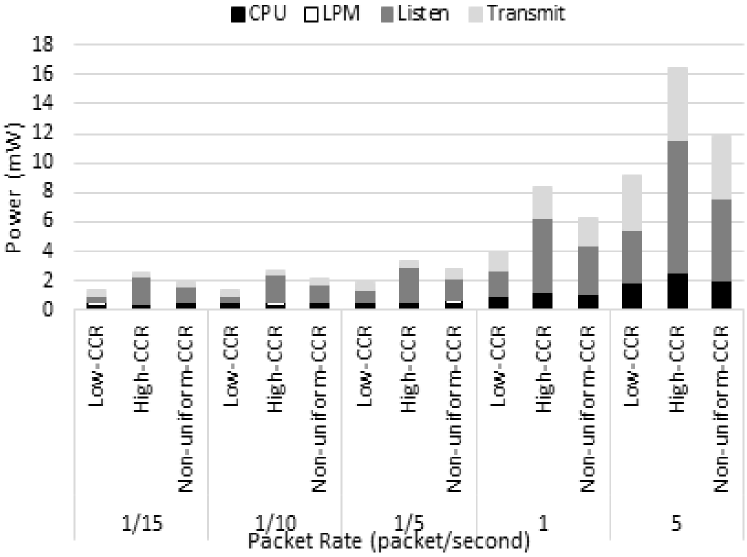

Figure 6. Average power consumption over packet rates

Figure 7 shows the average percentage of duty-cycle rate packet rates for all scenarios. The graph shows that Low-CCR achieves the lowest percentage of duty-cycle. This is because the sensor nodes assessing the channel at the least frequent that reduces the percentage of duty-cycle when compared to other scenarios. Otherwise, the High-CCR provides the highest percentage of duty-cycle. The Non-uniform-CCR provides average percentage of duty-cycle in between of Low-CCR and High-CCR scenarios.

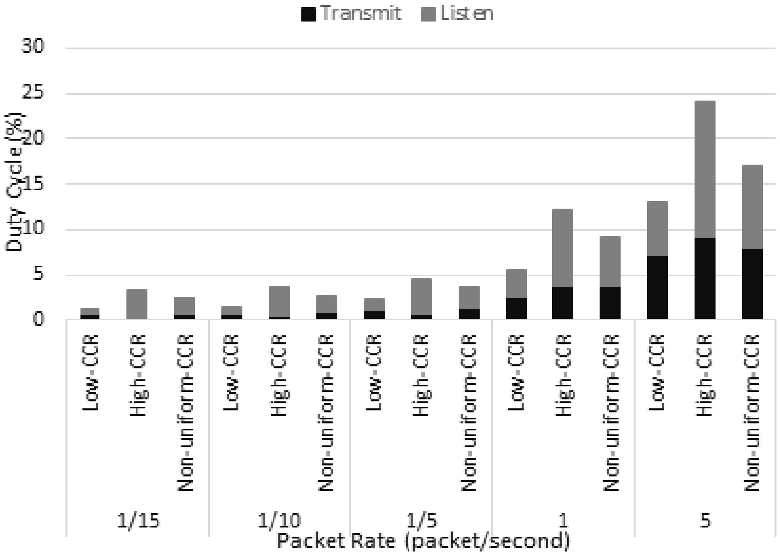

Figure 7. Average percentage of duty cycle over packet rates

6. CONCLUSION

This paper provides a study on the effect of non-uniform duty-cycle to the performance of ContikiMAC. The work are done using Cooja simulator. A random network topology consisting of 25 sensor nodes is established in the simulation environment. The sensor nodes are set to have non-uniform CCR values (Non-uniform-CCR). As the comparison, two uniform network scenarios are established: a low uniform CCR value (Low-CCR) and a high uniform CCR value (High-CCR). Based on the simulation results, the Non-uniform-CCR provides performances in between Low-CCR and High-CCR scenarios in term of PDR, power consumption and percentage of duty-cycle. This findings will provide a useful information in designing an enhanced ContikiMAC that dynamically changes its duty-cycle based on the network conditions.

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