An Adaptive Energy Efficient MAC Protocol for Wireless Sensor Network

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1 RESEARCH PROBLEM

In last years, the wireless sensor networks (WSNs) have take the interest of researchers since they have a number of potential applications in many domains of daily-life such as environment monitoring, healthy monitoring, medicine, surveillance, military, etc. The innovation of digital electronics, micro controller, wireless communications have facilitated the development of small tiny devices with these characteristics: low-cost, low-power and multi-functional. Due to the small size and the difficult access of a sensor node, the power source has limited capacity and cannot be replaced (non-replaceable). Therefore, energy consumption is an important constraint in WSNs. Energy harvesting (from many natural environment resources such as the heating, the sun light, the wind etc.) provides an effective option to increase the lifetime of the sensor network but it is not a complete solution. In some cases, these resources are not enough to be ensure a sufficient reliability. Thus the reduction of energy consumption is still one important focus of research in WSNs domain.

The reduction in energy consumption can be considered in both software as well as hardware approach. As far as the hardware components are concerned, radio transceivers integrated circuit has kept important role in reducing energy consumption. The radio chips are classified into two types, one focuses on optimizing receive current consumption but the transmit current is higher such as 8mA for receive current and 25mA for transmit current. The second type keeps the balance between receive and transmit current, which are from 17mA to 19mA. Although the innovations of technologies in radio transceivers in term of reduction in energy consumption the transceivers are still required to be improved. In the software point of view, the protocols not only within a single layer but also through cross-layer have achieved major improvements for extending lifetime of the sensor node. Moreover, the impact of the software controlling the hardware (also called as firmware) is indispensable, so there is room for the software part of a sensor node to perform better. This thesis focuses on lower layers of WSNs, especially on the access protocols to reduce energy consumption.

2 OUTLINE OF OBJECTIVES

In the context of energy aware WSNs, the main causes of energy consumption are: collision, overheads, overhearing, idle listening (Bachir et al., 2010). Based on these causes of energy consumption, the various MAC protocols could be classified into these groups: reducing collision, reducing overheads, reducing overhearing, reducing idle listening. In these regards, our objective is to reduce energy consumption in approach of reducing idle listening. An energy-efficient MAC protocol for cooperative strategies in WSNs will be proposed. Our works are separated into two steps:

First step is to propose an adaptive energy-efficient MAC protocol for the direct communication between two sensor nodes. The receiver tries to adapt its wakeup interval according to the traffic of the sender.

Second step is to apply the MAC protocol proposed in first step to the cooperative strategies. In this approach, there is a cooperative relay node, which resends the data packet on demand of receiver if needed. The network prototype is described in the Figure 1. In cooperative strategy, the receiver needs to adapt with not only the sender but also the relay node.

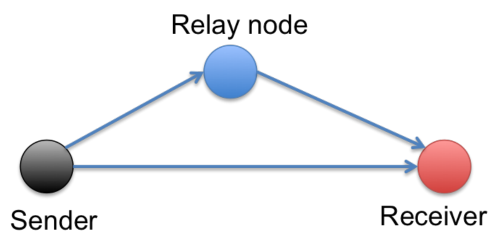


Figure 1: Cooperative relay strategy.

3 STATE OF THE ART

The Medium Access Control (MAC) layer is software integrated in a sensor node, which allows this node to efficiently share the wireless medium with others in the network. In MAC layer, the main causes of energy consumption are idle listening, overheads, overhearing and collision. Thus, in order to achieve the energy efficiency, these factors need to be optimized but there are trade-off between them. For example, reducing idle listening and collision requires extra synchronization and overheads, whereas, reducing the synchronization and overheads causes the waste of energy in collisions. In the context of energy-efficient MAC protocols, an important mechanism for reducing energy consumption is duty cycling. In this technique, the radio is turned on periodically, switching between awake and sleeping state. The duty cycle, which is measured as the ratio of time a node is awake to the total time, is used also to evaluate the performance of a protocol. The recent duty cycling MAC protocols can be grouped into two types: synchronous and asynchronous.

The synchronous duty cycling MAC protocols (such as SMAC(Ye et al., 2002), TMAC(van Dam and Langendoen, 2003)) reduce energy consumption by synchronizing the sleep & wakeup time of sensor nodes. After the synchronization, the idle listening problem is resolved but in the synchronization process, sender and receiver must exchange control packets. As an example in SMAC, the control packets CTS/RTS/SYNC are sent between sensor nodes to synchronize. In addition, using fixed time (time slot) for sleeping and listening state is inefficient with variable traffic rate.

In contrast, the asynchronous duty cycling protocols do not require any synchronization period and can be categorized into two groups: sender initiated and receiver initiated. In sender initiated MAC protocols, e.g. BMAC (Polastre et al., 2004), XMAC(Buettner et al., 2006), WiseMAC(El-Hoiydi and Decotignie, 2004), the sender initiates the communication by sending the preamble-sampling packet before a data transmission to notify the receiver of upcoming packet. Instead of using long preamble as in BMAC, XMAC protocol uses the series of short preamble packet and ACK packet is used just right after the reception of first preamble packet from receiver side to signify this sensor node is awake. On the other hand, the preamble-sampling packet is replaced by wakeup beacon, which is sent from receiver in the receiver initiated MAC protocols such as PW-MAC(Tang et al., 2011), RICER(yi A. Lin and Rabaey, 2004), RI-MAC(Sun et al., 2008), TAD-MAC(Alam et al., 2012). The wakeup beacon is shorter than preamble so the wireless bandwidth usage and collision are reduced. The basic principle of TAD-MAC protocol is described in. The figure is separate into two phases (i.e., before convergence and after convergence) that outline the results of a simple network with two nodes (Tx1 and Tx2) attempting to transmit data to a receive node. During the evaluation phase, before reaching the convergence, the receive node tries to adapt its wakeup-interval (I_{wu}) to the data transmission rate of each transmit nodes. After several wake-ups, the receive node will adapt its I_{wu} based on the statistics of traffic that it receives from each individual transmit node. The second phase, after convergence, indicates that the I_{wu} of receive node has been adapted to traffic of each transmit node in a way that the idle listening is minimal.

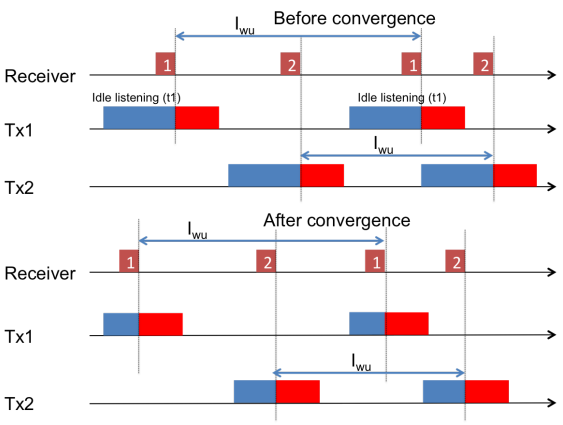


Figure 2: TAD-MAC protocol.

4 METHODOLOGY

To design energy-efficient WSNs, we must be able to explore all the parameters idle-listening, overheads, overhearing and collision (Bachir et al., 2010). The general methodology that can be applied to this exploration is shown in Figure 3. We consider the con-

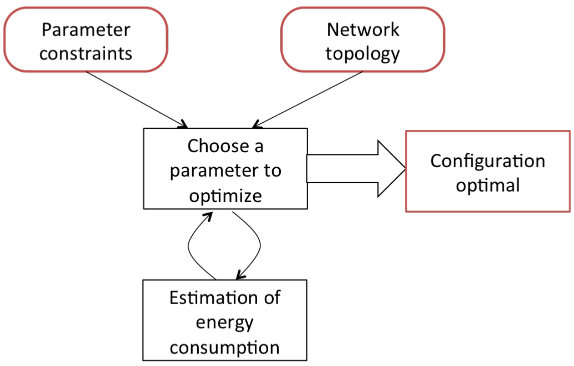


Figure 3: General methodology.

text of an already established network, not in the network development phase and the network topology is fixed. With this predefined network topology, we choose one parameter to optimize and observe the influence on other parameters by estimating energy consumption. After several repetitions, we can find a set of optimal parameters. To evaluate the performance of proposed protocol, TAD-MAC is chosen and implemented also to compare the simulation results.

5 STATE OF RESEARCH

5.1 Introduction

In a WSNs platform, typically, the radio transceiver consumes most of energy. The radio activities are controlled by Medium Access Control (MAC) layer. Therefore, it is necessary to design an energy-efficient protocol suitable for WSN. In the context of energy-efficient WSN, low duty-cycle protocols such as preamble sampling MAC protocols are very efficient for low traffic applications because these protocols improve the lifetime of the network by reducing the unnecessary energy waste. In the first step of our work, we proposed an adaptive energy-efficient MAC protocol called FTA-MAC (Fast Traffic Adaptive). FTA-MAC is an asynchronous duty cycling protocol with receiver initiated mechanism.

5.2 FTA-MAC Protocol Design

The basic principle of FTA-MAC is described in Figure 4. As other receiver initiated protocols, the receiver sends the wakeup beacon packet right after its wakeup to notify to other sensor nodes. But unlike TAD-MAC protocol, in FTA-MAC, the Wakeup Beacon (WB) does not contain the destination address, it uses broadcast WB. At the sender side, when it receives WB from the receiver, the sender senses the wireless medium for an interval of time called CCA (Channel Clear Assignment) to make sure that the channel is free to send the data. Normally the time of CCA is fixed as in other MAC protocols, but for FTA-MAC protocol, if the CCA is fixed, there exist collisions caused by broadcast WB. In the case there are two or more senders, which receive a same WB, they will be in conflict for data transmission. To avoid this collision, a function is proposed for senders to calculate the time of CCA each time they receive the WB as

$$t_{CCA} = t_{CCAmax} \cdot \left(1 - \frac{idle}{t_{WBmax}}\right) \quad (1)$$

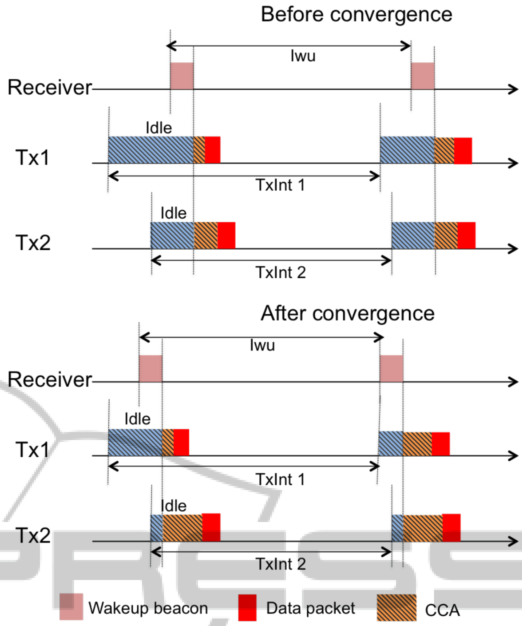


Figure 4: Basic principal of FTA-MAC protocol.

where t_{CCAmax} is the constant value maximal for the time of CCA, *idle* is the interval of time that the sender waits for WB and t_{WBmax} is the constant value for the maximal time waiting WB.

The main principle of FTA-MAC protocol is to adapt the wakeup interval (I_{wu}) of the receiver according to the data transmission rate of each transmit node. A Traffic Status Register (TSR) is used to store the status of data transmission in receiver. Each time the receiver receives a data packet, a *bit 1* is inserted into TSR by shifting left one bit. In contrast, if the receiver does not receive a data packet in one wakeup, the *bit 0* is inserted. A list of TSR called TSR-Bank is used to estimate the data transmission of all neighbor nodes as in Figure 5. The next I_{wu} is calculated by an adaptive function as

$$I_{wu}(i+1) = \begin{cases} I_{wu}(i) + n_0(i).t_{ref} & \text{TSR(i) = 0} \\ \frac{\sum_{j=k}^{i} I_{wu}(j) + idle_k - idle_i}{wbMissed+1} & \text{TSR(i) = 1} \end{cases} \quad (2)$$

where $n_0(i)$ is the number of bits 0 in TSR, t_{ref} is the system clock factor, k index stands for the last moment when the receive node received data from sender, $idle_i$ & $idle_k$ are the idle time of sender for two last time it received WB and *wbMissed* is the number of wakeup without receiving WB. The three values $idle_k$, $idle_i$ and *wbMissed* are calculated in sender side and sent to receiver by including in data packet. The two first bytes in the payload part of data packet are used to store these values. These parameters are described more detail in Figure 6 and Figure 7.

5.3 Implementation

In this section, the implementation details of FTA-MAC protocol in a network simulator are explained. One of the network simulators, which support wireless sensor network, is OMNeT++/MiXiM. OMNeT++ is an object-oriented modular event network simulation and it provides the infrastructure for writing simulations with the component architecture. All elements are called modules and the modules can be connected via gates (or ports) and communicate by exchanging messages. MiXiM is a modeling framework for wireless network (WSNs, body area network, ad-hoc network, vehicular network, etc).

In OMNeT++/MiXiM, there is a definition of network node called *WirelessNodeBattery* which contains the specific elements for a sensor node such as the network interface *WirelessNicBattery*, the power supply *SimpleBattery* and the module *BatteryStats* which calculates the consumption of energy for each element. The main implementation of FTA-MAC protocol is **FTAMACLayer**, which is a module of the MAC layer that is integrated in a new network interface **NicFTAMAC** (based on *WirelessNicBattery*). As the other modules in MiXiM, **FTAMACLayer** contains the gates to connect with other modules/other layers. The messages are used not only as the packets to send between the layers of a sensor node or between two nodes but also as the events to change the state of a node. The state machines

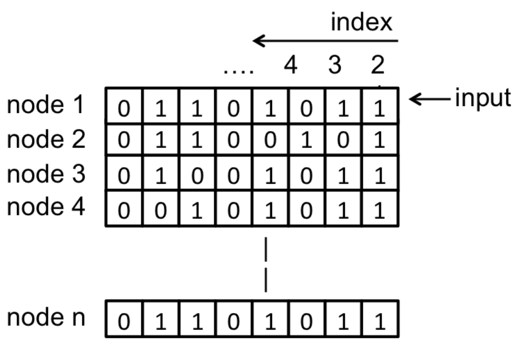


Figure 5: TSR-Bank containing N registers for N neighbor nodes.

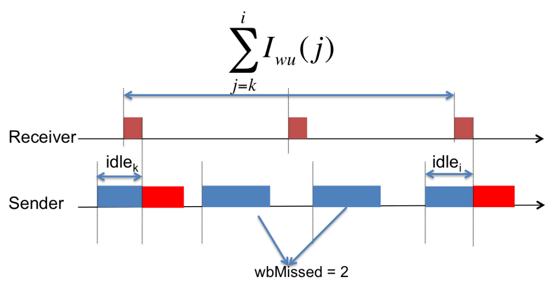


Figure 6: Adaptive function to calculate I_{wu}.

Table 1: Simulation configuration.

	Scenario 1	Scenario 2	Scenario 3
simTime	1000s	1000s	1000s
t_{WBmax}	250ms	500ms	500ms
TxInt	500ms	500ms	variable

of transmit node and receive node shown in Figure 8(a) and 8(b) describe all the self-messages and the network packets that are used in **FTAMACLayer** to change the state of a sensor node.

The new structure of MAC frame is proposed in Figure 7. The two first bits of *frame control* byte (the first byte of MAC frame) are used to define the type of frame (WB, DATA or ACK). In WB frame, the address information needs 4 bytes to store only the source address because the WB is broadcast frame. The size of WB frame is very small, only 5 bytes of length (1 byte for frame control and 4 bytes for source address) so the energy consumption is reduced. In DATA frame, the frame length is displayed in 6 bits of *frame control* byte and the two first bytes of payload part are used to store the ***idle*** and ***wbMissed*** variables.

5.4 Performance Evaluation

To evaluate the performance of FTA-MAC protocol, the simulation scenarios are executed in OMNeT++ and compare with TAD-MAC. The configuration of simulation scenarios are shown in Table 1. In each scenario, the value I_{wu} is variable to study the performance of protocol by observing the parameters: convergence time of I_{wu}, energy consumption, specially, in the scenario 3, the traffic is variable.

The first results in Figure 9(a) and 9(b) show that FTA-MAC reach the steady state faster than TAD-MAC, specially, in scenario 1 with the t_{WBmax} is 250ms, the convergence value of I_{wu} in TAD-MAC is wrong if the value I_{wu} initial is equal or greater than 700ms. It converges at 750ms instead of 250ms

When comparing energy consumption, FTA-MAC can optimize the energy consumption in transmit node (as in Figure 10(a)) but on the other side, in

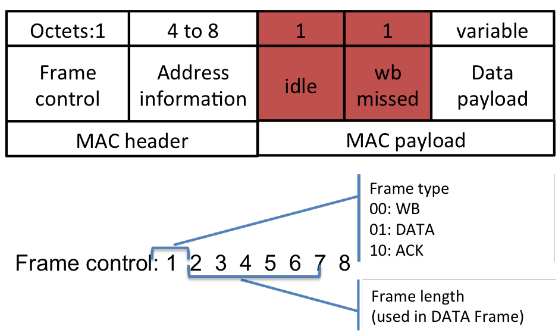
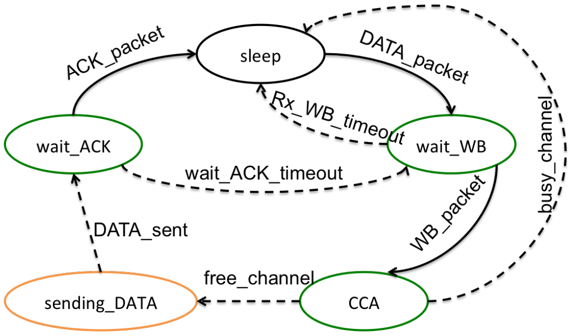
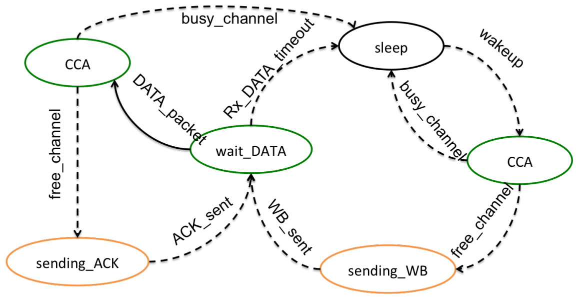


Figure 7: New MAC frame structure.



(a) transmit node.



(b) receive node.

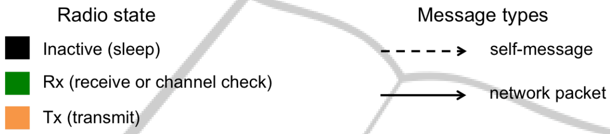
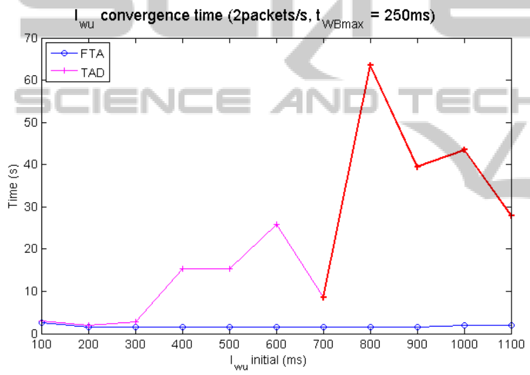
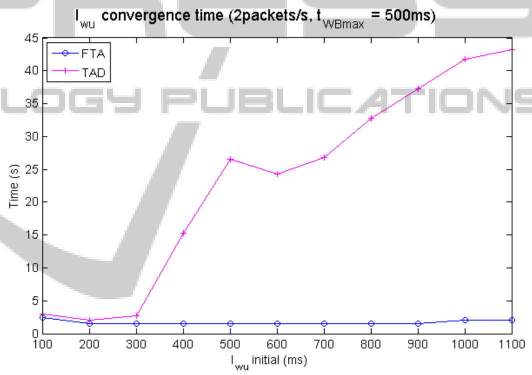


Figure 8: State machine of *FTA-MAC*.



(a) scenario 1.



(b) scenario 2.

Figure 9: I_{wu} convergence time.

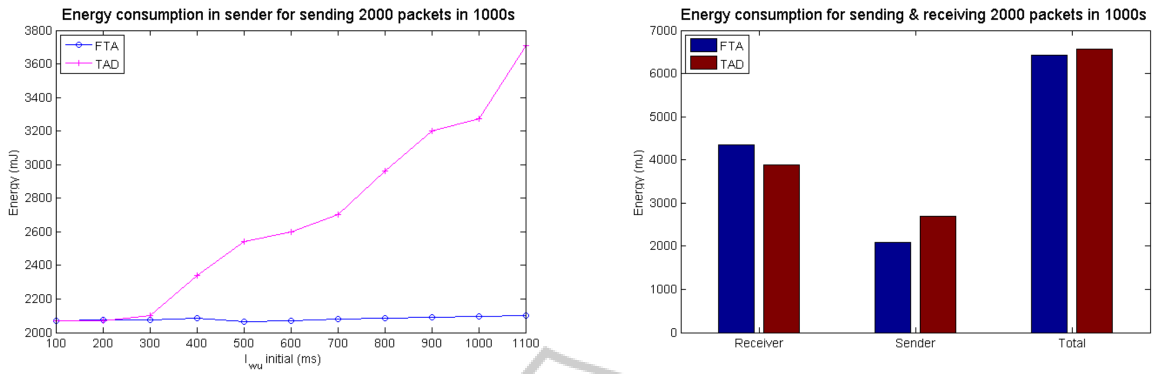
receive node, FTA-MAC consumes more energy. This is because the receiver needs to keep awake longer to wait more for data packet so it cannot switch off the radio right after sending the ACK packet. The result of comparing energy consumption in Figure 10 points on the reducing of energy consumption in the network (the total of transmit node and receive node) is efficient in FTA-MAC.

The results of simulation scenario 3 shows that FTA-MAC protocol works well for variable traffic. The Figure 11(b), 11(c) and 11(d) are zooms of Figure 11(a) at the moment when traffic is changed. After few wakeups, the receiver can adapt to the new traffic rate of sender.

6 CONCLUSION AND PERSPECTIVE

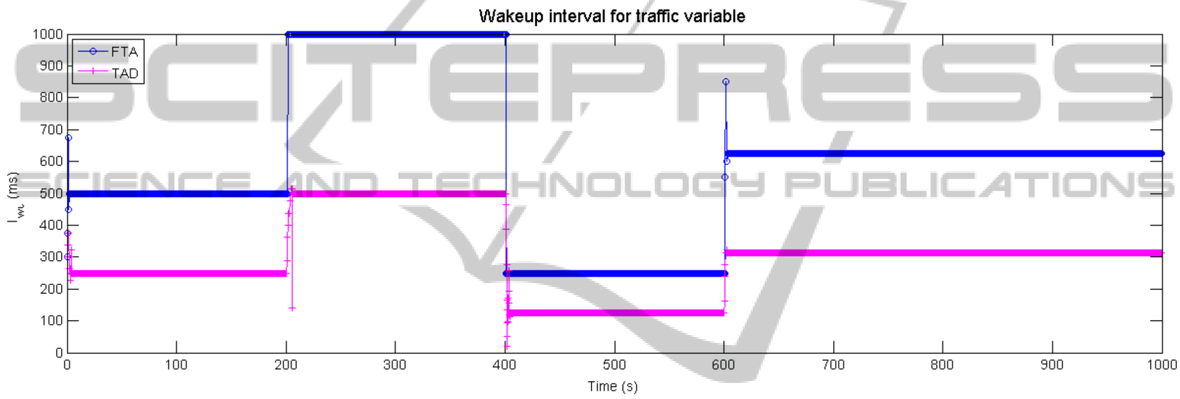
In the first step of our works in this thesis, we proposed an adaptive energy-efficient MAC protocol for WSNs. In this protocol, the sensor node adapts its wakeup interval dynamically with the traffic load it receives and consequently optimizes the energy consumption. This protocol is implemented in network simulator OMNeT++ and the simulation result shown that FTA-MAC outperforms other MAC protocols such as TAD-MAC.

In last years, cooperative technology gains some success result in term energy-efficient for WSNs. Our future works will focus on the cooperative strategies and try to apply in FTA-MAC.

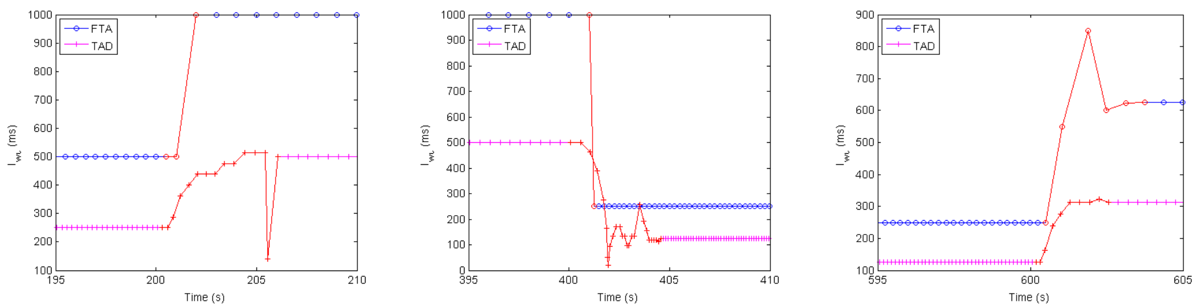


(a) Energy consumption in sender. (b) Energy consumption in network.

Figure 10: Energy consumption for sending 2000 packets in 1000s.



(a)



(b) (c) (d)

Figure 11: I_{wu} with variable traffic.

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