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A Queue-Based Energy Saving Scheme for Mobile Embedded Systems with Multiple Radio Interfaces

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Abstract

Mobile embedded systems (MESs) with multiple radio interfaces such as WLAN, Bluetooth and ZigBee will play an important role in future connected network environments. MESs with a conventional mechanism are assumed to maintain the power-on state of multiple communication modules to communicate with each other at any time. This 'always-on' operation wastes the energy of MESs and decreases the lifetime of MESs. To reduce the energy consumption in MESs, we propose an energy-aware communication module selection scheme through ZigBee paging in MESs. The energy-aware communication module selection scheme predicts energy consumption for transmitting the given data and selects a communication module which consumes the minimum energy. A ZigBee paging mechanism is used to turn on or off the corresponding communication modules when they have data to send or no data to send, respectively. Experimental results show that the proposed energy-aware communication module selection scheme through ZigBee paging reduces energy consumption by 6%, 93%, and 97% for WLAN, Bluetooth, and ZigBee, respectively, compared with the conventional mechanism.

Keywords: Mobile embedded system, energy saving, WLAN, WPAN, IEEE802.11, Bluetooth, ZigBee.

INTRODUCTION

Future connected networking services will be provided through heterogeneous networks which can be combined two or more homogeneous networks such as wireless personal area networks (WPANs) and wireless local area networks (WLANs). In this connected network environments, mobile embedded systems (MESs) can play an important role to provide various services. One of main obstacles in realizing the connected networks is the short battery life-time of mobile devices. It is found that the major part of energy consumption is to communicate by Wi-Fi WLAN and, in particular, the most energy is consumed in the idle state of WLAN [2]. One approach to extend the battery life-time is to exploit multiradio interfaces of mobile devices. An event-driven energy saving strategy called Wake-on-Wireless is to use second low power radio as a wake-up channel for primary wireless interface [3]. It utilizes the second wireless interface as only a control channel. It does not fully utilize the capability of the second interface. CoolSpots was proposed to reduce the energy consumption of wireless devices [2]. However, the selection policy for wireless radio interfaces did not consider the network condition and the amount of energy consumption for transition to different wireless radio interfaces.

In this paper, we propose a new access-network selection scheme, called queue-occupancy based energy-saving scheme, when mobile nodes have both IEEE 802.11 and Bluetooth radio interfaces in an overlaid network environment of WLAN and WPAN. IEEE 802.11 WLAN is more energy-efficient to transmit a large amount of data than Bluetooth if we just consider the data transfer phase. However, the energy consumption in idle state is too high. If the idle period is too long, then it is desirable to shut down the IEEE802.11 WLAN interface. On the other hand, the energy consumption for transition to different wireless radio interfaces cannot be neglected and frequent transitions cause more energy consumption. The proposed queue-occupancy based energy-saving scheme adaptively determines a threshold value of queue occupancy considering both the transition energy and network condition. Using this threshold value, we determine when the IEEE 802.11 WLAN interface is powered on or off. Since the threshold value depends on varying network conditions, we present an energy consumption model by which we can estimate the amount of energy consumption for transmitting frames through the WLAN interface. The proposed model is based on the collision probability and channel utilization of WLAN. In order to evaluate the performance of the proposed queue-occupancy based energy-saving scheme, we run simulations in varying network conditions for various traffic patterns.

The rest of this paper is organized as follows. In Section 2, an overlaid network with WLAN and WPAN is presented. In Section 3, The access-network selection scheme, which is called a queue-occupancy based energy-saving scheme is proposed. In Section 4, to estimate the amount of the energy consumption for WLAN communications, an energy consumption model based on the collision probability and channel utilization of WLAN is presented. In Section 5, the performance of the proposed selection scheme is evaluated in terms of energy consumption and compared with that of other selection schemes. Finally, conclusions are presented in Section 6.

A FRAMEWORK OF AN OVERLAID NETWORK WITH WLAN AND WPAN

In this section, we present a framework of an overlaid network with WLAN and WPAN. In a connected network environment consisting of WLAN and WPANs as shown in Fig. 1, each mobile user has multiple radio interfaces which can be connected to the WLAN and WPAN. In this environment, mobile users can select the best access-network for their own objectives, such a power-saving and desired data rate. One of important issues in this network is how to manage each mobile user's connectivity information indicating which access-network is used for each mobile user. If a packet is destined to a mobile user, it can be properly delivered to the mobile user with this information.

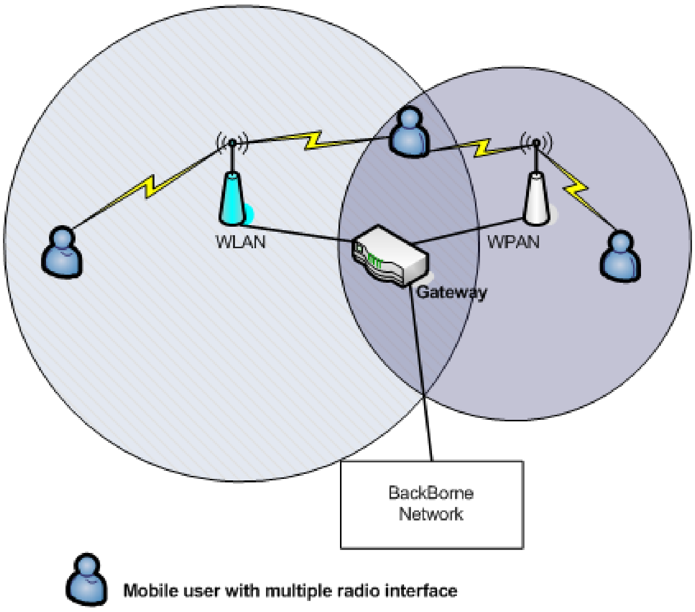


Figure 1: An overlaid network using both WLAN and WPAN

To solve this problem, we can use a gateway. The gateway is connected to all the access-networks and is used to manage the connectivity information. All the packets pass through this gateway. The decision to perform changing from a network to the other network, which is called a vertical handover and to select an access-network is made by mobile nodes according to a access-network selection scheme. If a mobile user decides to perform a handover, it needs to exchange a handover request message and handover acknowledge message with the gateway. The connectivity information is managed and updated at the gateway using the handover request message.

Fig. 2 shows the flowchart that a mobile node maintains a connection and performs a handover procedure. The mobile node periodically monitors the currently connected link and other alterative links. If the link quality is severely changed, then the best access-network is newly selected under a given policy and a handover procedure is started. If the mobile node decides a handover to another access-network, then it sends a handover request message to the gateway. If the gateway receives the handover message, then it updates its own routing table to route the packet destined to the node via the newly selected access-network. Fig. 3 shows the exchange of the handover related messages.

PROPOSED QUEUE-BASED ENERGY SAVING SCHEME

In this section, we propose an access-network selection scheme, called a queue-occupancy based energy-saving scheme, when a mobile node has both WLAN and WPAN radio interfaces. We consider the IEEE 802.11 as a WLAN access technology and bluetooth as a WPAN access technology. It is assumed that the queue is shared by multi radio interfaces. The packet in the queue are transferred through one of the radio interfaces.

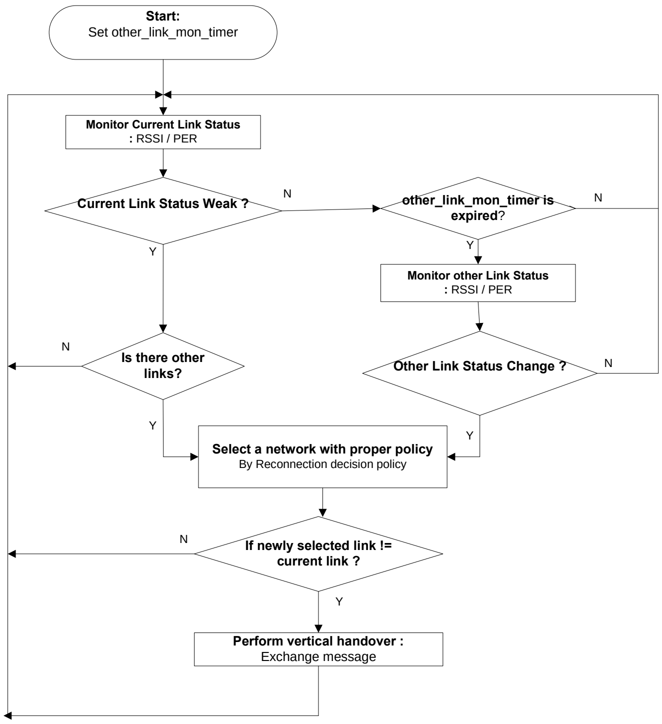


Figure 2: Vertical handover procedure

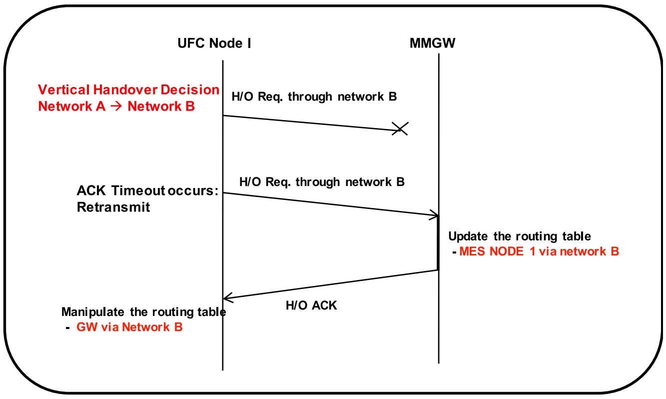


Figure 3: Exchange of handover messages

IEEE 802.11 WLAN is more energy-efficient to transfer data if we consider only transfer phase. However, they consume approximately 750 mW even in IDLE state. On the other side, Bluetooth needs more energy to transmit data than IEEE802.11 WLAN but consumes less energy in IDLE state. Thus, it may be rather proper to shut down the WLAN interface and use Bluetooth interface when the node has little data to transmit. However, the transition energy for power on/off cannot be neglected. In an experiment [6], [7], it was reported that the transition energy for power on/off consumes approximately 1575 mJ. This is the motivation of the proposed queue-occupancy based energy-saving scheme. The basic idea of the proposed scheme is to shut down the WLAN interface as long as possible considering the transition energy and current network condition like traffic load.

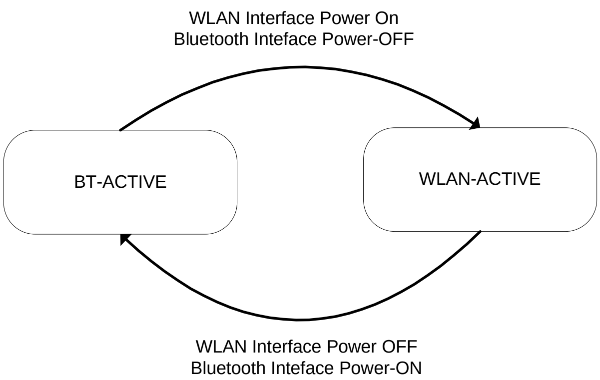


Figure 4: State transition diagram

Fig. 4 shows the state transitions of a mobile node. In BT-ACTIVE state, the Bluetooth interface is used to connect to the network, while an IEEE802.11 interface is shutdown. Otherwise, in WLAN-ACTIVE state, the WLAN interface is used to connect while the Bluetooth interface is shutdown. If there is a more energy-savable state than for the current state, a state transition occurs using the handover procedure presented in Section 2.

There are two cases of state transitions: (i) BT-ACTIVE state to WLAN-ACTIVE state and (ii) WLAN-ACTIVE state to BT-ACTIVE state.

Transition from BT-ACTIVE state to WLAN-ACTIVE state

The threshold value occupancy is set to a value so that condition 1 is satisfied

$$E_{BT}^{TX}(\vec{Q},\vec{N}_{BT}) \geq E_{WLAN}^{TX}(\vec{Q},\vec{N}_{WLAN}) + E_{BT\to WLAN}^{TR}, \quad (1)$$

where $\vec{Q}$ denotes the queue state, $\vec{N}_{BT}$ is the network condition of Bluetooth, $\vec{N}_{WLAN}$ is the network condition of WLAN, $E_{BT}^{TX}(\vec{Q},\vec{N}_{BT})$ represents the amount of energy for transmitting data in Bluetooth interface, $E_{WLAN}^{TX}(\vec{Q},\vec{N}_{WLAN})$ represents the amount of energy for transmitting data in WLAN interface, $E_{BT\to WLAN}^{TR}$ denotes the amount of energy for transition from BT ACTIVE to WLAN ACTIVE state.

The condition 1 implies that the expected energy consumption for transmitting all packet in the queue in the current Bluetooth network condition is larger than the required energy for transition to WLAN-ACTIVE state and transmission of all data through WLAN access-networks.

The node monitors the occupancy of queue periodically and if the queue occupancy exceeds the threshold value, then transition to WLAN-ACITVE state occurs. Our proposed scheme assures that the state transition should be performed only if the energy gain is guaranteed. Thus, the unnecessary transitions can be prevented. Since the threshold value depends on network conditions like traffic load, in order to set the threshold value of queue occupancy properly, we need to estimate the amount of the energy consumption for each state and transition from one state to the other state. In Section 4, the energy consumption model will be presented.

Transition from WLAN-ACTIVE state to BT-ACTIVE state

A state transition occurs when the following conditions are satisfied:

$$Q_{len} = 0, \quad R_{in} > R_{th}, \quad (2)$$

where R_{in} is the incoming data rate into the queue and R_{th} is the threshold value. If there are pending data in the queue and the system is on WLAN-ACTIVE state, it is better to transmit the pending data using the WLAN interfaces. It is because the pending data is straightly transmitted without idle period of WLAN. Therefore, the WLAN needs less energy than the Bluetooth for transmitting.

If the queue is empty, we must determine if the transition is performed or not. It depends on the future traffic pattern that we need to estimate. For this estimation, the proposed scheme monitors the current incoming data rate. If the incoming data rate is lower than the threshold value, then we need to have a state transition to BT-ACTIVE state.

MODELING ENERGY CONSUMPTION IN IEEE802.11

In the Bluetooth technology, since the radio resource for communication is reserved in a dedicated TDMA mechanism, its network condition seldom changed. This implies that the energy consumption to transmit a frame is predictable and is changed little. On the other hand, since IEEE802.11 WLAN is a contention-based access technology, its network condition varies and the energy consumption to transmit a frame also varies. Therefore, if we use the amount of energy consumption as a metric for the selection scheme, we need to expect the amount of energy consumption to transmit a frame in WLAN access networks.

We propose an energy consumption model for transmitting data using collision probability and channel utilization of WLAN. It is reasonable to use the collision probability and channel utilization as parameters because the Access Point (AP) can monitor the network and obtain these values with the aid of MAC layer. As described in Section 2, the gateway can collect and broadcast the network information such as collision probability and channel utilization. Therefore, each node can estimate the expected amount of energy consumption to transmit data using IEEE 802.11 WLAN. To estimate the amount of energy consumption, we can divide the energy consumption into three parts:

$$E = E_{BO,init} + E_{col} + E_{succ}, \tag{3}$$

where

$$E_{succ} = T_{FRAME}P_{TX} + T_{ACK}P_{RX} + (SIFS + DIFS)P_{IDLE}. \tag{4}$$

In (3), $E_{BO,init}$ is the amount of the energy consumption in the first backoff period to acquire the channel access. E_{col} is the amount of the energy consumption caused by collision events. E_{succ} is the amount of the energy used to transmit a frame successfully. In (4), T_{FRAME} and T_{ACK} denote the duration of transmitting a data frame and receiving its acknowledgement. $SIFS$ represents a short interframe space and $DIFS$ represents a distributed interframe space, as defined in [3]. P_{TX}, P_{RX}, and P_{IDLE} are the amount of energy consumption of transmission, reception, idle mode of WLAN, respectively.

In the initial backoff stage, the mean value of the size of backoff window is $W_{min}/2$ where W_{min} is the minimum backoff window. The channel utilization is interpreted as the probability that channel is busy, P_{util}, so that, the probability that channel is idle at a certain timeslot is $1 - P_{util}$. The event that the channel is idle occurs per $1/(1 - P_{util})$ timeslots. Therefore, the $E_{BO,init}$ is expressed as

$$E_{BO,init} = \frac{W_{min}}{2} \cdot \frac{1}{1 - P_{util}} T_{SLOT} P_{IDLE}, \tag{5}$$

where T_{SLOT} is the duration of a time slot that is a unit of backoff of WLAN.

E_{col} is given in (6). Since the collision event that occurs more than two times consecutively is rare, we only consider up to two consecutive collisions. In (6), the time duration in backoff state is also considered and it is expressed as channel utilization in the same manner with the initial backoff stage:

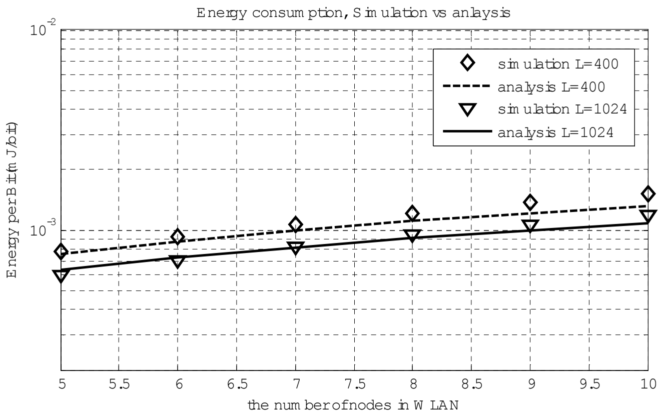
$$\begin{aligned} E_{col} = P_{col}(1 - P_{col}) \Big(& T_{FRAME}P_{TX} + \frac{2W_{min}}{2} \\ & \cdot \frac{1}{1 - P_{util}} T_{SLOT} P_{IDLE} \Big) \\ & + P_{col}^2 (1 - P_{col}) \Big(T_{FRAME}P_{TX} \\ & + \frac{4W_{min}}{2} \cdot \frac{1}{1 - P_{util}} T_{SLOT} P_{IDLE} \Big), \end{aligned} \tag{6}$$

where P_{col} is the collision probability.

To validate our model, we run simulations in the IEEE802.11 environment with the parameters listed in Table I. We obtain the required energy to transmit 1 bit, energy per bit (EPB), for varying the number of WLAN users. Fig. 5 shows the EPB versus the number of WLAN users. The proposed energy consumption model agrees with the simulation results. As the number of WLAN users increases, the EPB increases, also. It is because the number of collisions and retransmissions increases. It yields much energy consumption for successfully transmitting data.

SIMULATION RESULTS AND DISCUSSION

To evaluate the proposed queue-occupancy based energy saving scheme, we run simulations for several traffic patterns and network conditions and then compare the performance of the conventional selection schemes such as BT-FIXED, WLAN-FIXED, BANDWIDH-X [2]. The WLAN-FIXED scheme uses only a WLAN interface and the BT-FIXED scheme uses only a Bluetooth interface. In the BANDWIDH-X scheme, if the output packet rate exceeds the threshold, then the WLAN interface is selected. Otherwise, the Bluetooth interface is selected.



Fgure 5. Energy per bit vs. number of WLAN users

Table I. Parameters of IEEE 802.11

Parameter	Value
MAC header / PHY header	272 bits / 128 bits
ACK	112 bits + PHY header
Channel bit rate	
Slot time / DIFS / SIFS	20 usec / 50 usec / 10 usec
W_{min} / W_{max}	32 / 1024

The performance index of the proposed selection scheme may depend heavily on traffic patterns. We investigate the effect of traffic patterns. To expect the performance in a real environment, we use HTTP, FTP traffic models used to evaluate the system performance in 3GPP [8].

The simulation parameters of WLAN are given Table I. The energy consumption profile listed in Table II is referred from the experiment results in [6], [7]. We assume that when a Bluetooth interface is used, the throughput at IP-Layer is fixed to 150 kbps. The threshold value of the BANDWIDH-X scheme is set to 140 kbps. We denote the proposed queue-occupancy based energy-saving scheme as QLEN-X.

Fig. 6 shows the normalized energy consumption for varying the number of the full-queue nodes in WLAN when the FTP-BULK traffic with a series of 2 Mbytes is continuously generated with an interval of 10 sec. The BT-FIXED scheme is very efficient. However, the delay is much longer, compared with that of other schemes. In the WLAN-FIXED scheme, the most part of energy is consumed during IDEL period. In the BANDWIDHT-X and the proposed QLEN-X schemes, the energy is consumed little during WLAN-IDLE time. However, the transition energy is additional required. Approximately 20% energy is reduced, compared with WLAN-FIXED policy when the number of full-queue nodes is small. The larger number of full-queue nodes, heavier the traffic load is. As the WLAN access-network condition becomes bad, the proposed QLEN-X scheme uses the Bluetooth interface to transmit data. On the other hand, the BANDWIDHT-X policy only uses the WLAN interface to transmit data so that the energy consumption become larger when the WLAN access-network condition is bad.

Table II. Energy profile for radio interfaces

	WLAN	Bluetooth
Idle / Tx / Rx Power (mW)	750 / 1050 / 950	105 / 198 / 198
Power On / Off Energy (mJ)	1575 / 1575	95.4 / 95.4

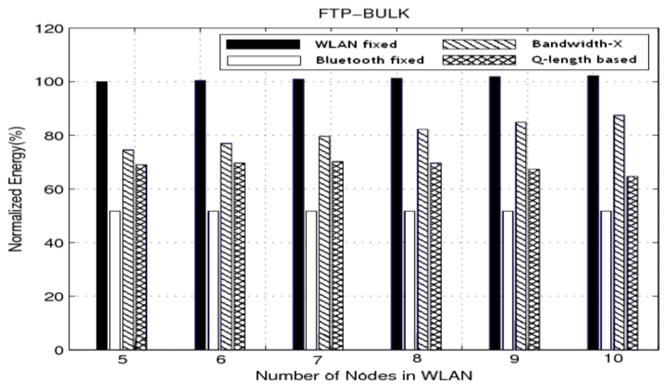


Figure. 6. Normalized energy consumptions using FTP-BULK traffic

Fig. 7 shows the energy consumption versus the rate in a Poisson traffic environment. When the rate of Poisson traffic is more than 140 kbps which is the threshold value of the BANDWIDHT-X scheme, many transitions occur in the BNADWIDTH-X scheme and, thus the energy consumption is sharply increased.

Fig. 8 shows the benefit of mutli-radio systems in order to reduce the energy consumption. For the FTP and HTTP traffic patterns, there is much longer reading time (30 sec ~ 60 sec), and the idle time is much long. In these cases, the saved energy, compared with the WLAN-FIXED scheme, is more than 50%. For the HTTP traffic pattern, a small chunk of data is generated bursty and it causes a transition in the in the BANDWIDTH-X scheme.

CONCLUSION

In this paper, we proposed a new access-network selection scheme called a queue-occupancy based energy-saving scheme. We first derived an energy consumption model based on the collision probability and channel utilization of WLAN. We evaluated the proposed queue-occupancy based energy saving scheme compared with the conventional schemes through simulations for various traffic patterns. The results show that we can save much energy for a traffic pattern with long idle time by using the proposed scheme and BANDWIDTH-X scheme. It was also shown that the proposed scheme performs less transitions compared with the BANDWIDTH-X scheme.

ACKNOWLEDGMENT

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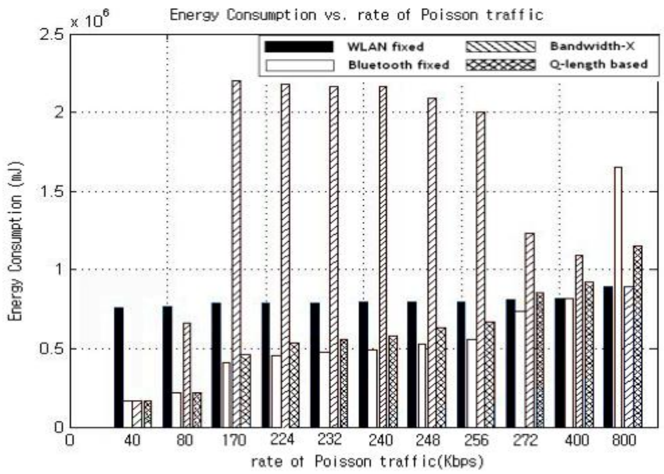

Figure. 7: Energy consumption vs. arrival in Poission traffic environment

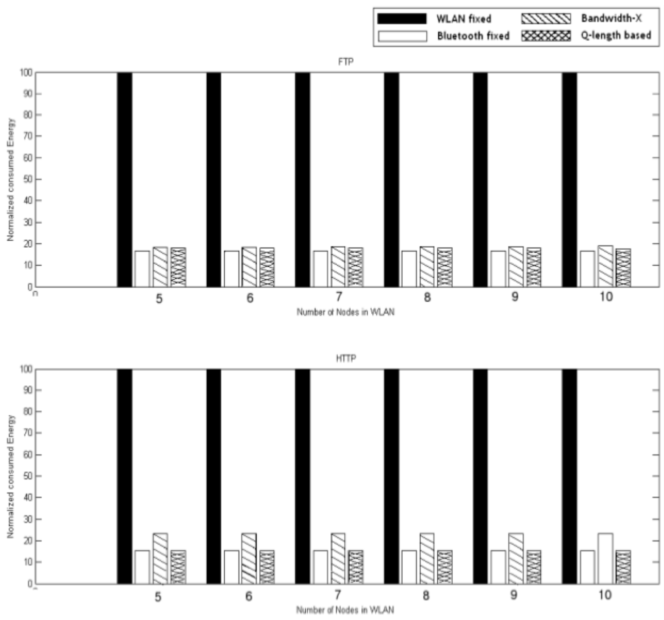

Figure 8: Energy consumption vs. number of nodes in WLAN

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