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NDNC-BAN: Supporting rich media healthcare services via named data networking in cloud-assisted wireless body area networks

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ABSTRACT

Nowadays, Wireless Body Area Network (WBAN) is broadly utilized for health monitoring and remote medical care. When the physiological information collected in WBAN is distributed to cloud computing platform, a new healthcare service mode is enabled by "cloud-assisted WBAN", where user's body signals can be stored, processed, managed and analyzed over a long-term period. Though the provisioning of healthcare services is largely enhanced via cloud-enabled technologies, more challenging issues are raised due to the increased user's requirements on quality of experience (QoE) in terms of user mobility, content delivery latency, and personalized interaction, etc. In order to tackle these challenges, this paper presents various solutions including: (1) a novel integration of WBAN with Long Term Evolution (LTE) to support high user mobility; (2) an efficient scheme to distribute contents by leveraging the emerging named data networking (NDN) technology, to support rich media healthcare content delivery without service interruption while achieving low cost and bandwidth saving; (3) the use of adaptive streaming to adjust suitable content size according to the dynamic bandwidth. The experimental results conducted by OPNET verify the viability of NDN and adaptive streaming to support the healthcare services involving the transmissions of rich media contents between WBAN and internet.

1. Introduction

Wireless Body Area Network (WBAN) or Body Area Network (BAN) contains a set of wearable body sensor nodes which are typically placed on or around human body, collecting data and sending it to access point through various wireless technologies, among which Zigbee is mostly used.

Though the network parameters are fine-tuned to meet particular quality of service (QoS) requirements in Zigbee based intra-BAN and inter-BAN [6], existing network architectures are hard to support high mobility for both patients and physicians due to the intrinsic features of low data rate and channel dynamics. Nowadays, this problem can be alleviated by using mobile device, such as iPhone/iPad, android phone, even a robot, as a personal server to interconnect intra-BAN with outside world. The mobile device should have at least two interfaces, i.e., one Zigbee interface to communicate with Zigbee-enabled body sensor nodes within intra-BAN, the other interface to forward body signals to external network.

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Once the user's health status is delivered to cloud platform, a new healthcare service mode can be supported by cloud-enabled technology [17]. The proposed architecture of cloud-assisted WBAN is shown in Fig. 1, where the basic data transmissions are divided into the following three stages:

- User's physiological parameters such as heart rate, respiratory rate, blood pressure, oxygen saturation, etc., will be collected by body sensors, and forwarded to cloud by mobile device in an on-demand fashion.
- User's physiological status is stored, processed, managed and analyzed over a long-term period in the cloud platform.
- The physiological information stored in cloud platform can be distributed to hospital, doctor, nurse or immediately family members, etc.

Since cloud computing provides a low-cost approach to support extensive data storage and computing-intensive analysis of healthcare big data, the provisioning of healthcare services is largely enhanced via cloud-assisted WBAN. However, more challenging issues are raised due to the increased user's requirements on quality of experience (QoE) in terms of user mobility, content delivery latency, and personalized interaction, etc. In order to illustrate these challenges, we give three scenarios where the communications and QoS are hard to be supported by the conventional WBAN architecture:

- For the application of *medial emergency handling* (e.g., medical emergency response during earthquake), various medical personnel need to get patient's comprehensive physiological data in a timely fashion for fast analysis and diagnosis. However, fetching patient's data by traditional Client/Server (C/S) mechanism consumes lots of energy from the patient's portable device by multiple transmissions of the same content [7,10]. Due to the intrinsic resource-poor feature of the portable device (e.g., a mobile phone), the dissemination of the time-sensitive data streams suffers from undesired performance in terms of end-to-end delay, packet delivery ratio and throughput, etc. Named data networking (NDN) can alleviate such problems, and enable different rescue team members to obtain patient's vital signals simultaneously at an earliest moment.
- In *3D Telehealth Education Application* as shown in Fig. 2, let's assume that a physician is doing some surgery for a patient, while the whole process is recorded into 3D tutorial video under a permission with the patient before the operation. The video contents are continuously uploaded to a remote server associated with an online medical school, where the students can request the video contents for studying. In case that a certain number students are downloading the real-time video contents during the operation, NDN will offer opportunities to save bandwidth.
- In the application of *help-on-demand healthcare video delivery*, for the first-time mother, the requested content can be tutorial video of breast feeding. For an autism patient, the requested data can be a personalized social media content. For a patient just moving out of hospital, the requested content can be a tutorial video to provide guidance of rehabilitation therapy, etc. Within a community, if the number of similar interests is large enough, NDN can amortize the cost of introducing the cache and exhibit its advantages extensively.

In order to address the issues raised in the above scenarios, we propose a novel architecture named by NDNC-BAN to support rich media healthcare services via NDN in cloud-assisted WBAN, and the following mechanisms are presented in this paper:

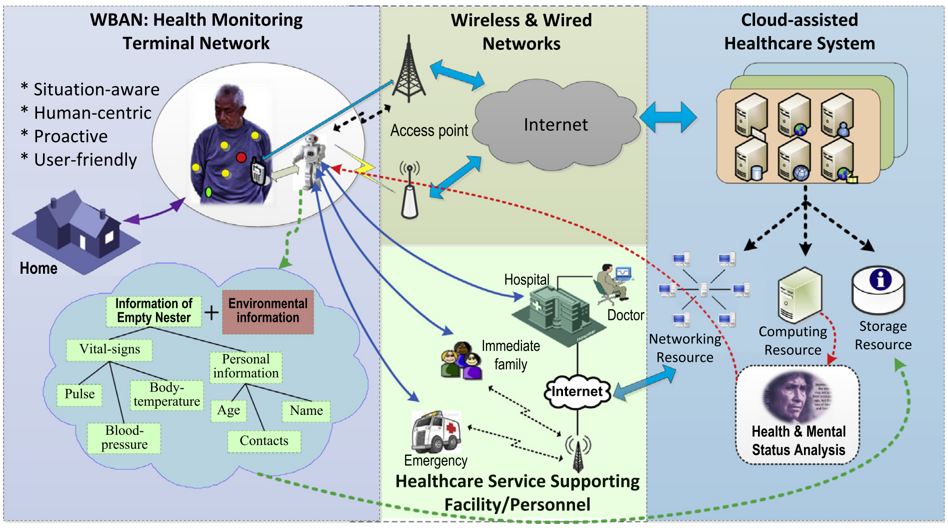


Fig. 1. The use of mobile device as an integral interface to interconnect BAN with outside world.

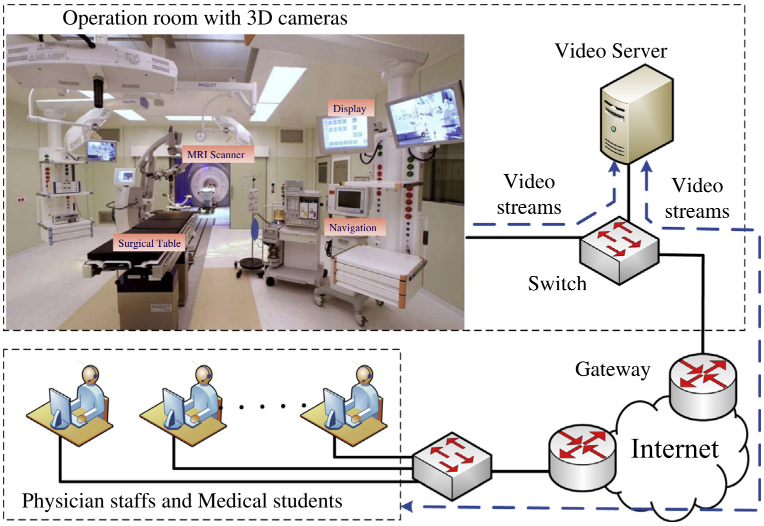


Fig. 2. A typical 3D telehealth scenario.

- *Support High User Mobility*: we propose a novel integration of WBAN with Long Term Evolution (LTE). This paper considers data collected from body sensors are interested not only by physicians but also by a number of different end users at the same time in a real time fashion. Especially, we allow both patients and physicians to moves freely. Thus, due to the flexible bandwidth supported by LTE technology, diversity of the applications and services in healthcare system are developed. We propose that a smart-phone serving as the gateway of patient data can bring comfortableness for hospitalized patients mainly in the following points: (i) smart-phone can be a communication terminal for the patient while being able to appropriately process various physiological data, (ii) smart-phone can utilize the resources of the cellular network for long distance delivery for the sensed data, and (iii) patient's mobility is guaranteed.
- *Support QoS for Multi-users to Request Healthcare Contents*: When various individuals inquire the patient's data, NDN technology is deployed to achieve resources saving, such as energy, bandwidth, etc.
- *Efficient Content Delivery from Cloud*: We leverage the emerging NDN to design an efficient and robust scheme to deliver on-demand content from cloud, to support high quality help-on-demand healthcare video delivery without service interruption while achieving low cost and bandwidth saving. In addition, the technology of adaptive streaming is employed to adjust suitable resolution of the on-demand video based on the dynamic bandwidth.
- *Flexible and Personalized Interaction*: The personalized health related data of elderly people will be stored and analyzed in the cloud-assisted healthcare system, which will properly provide expert-level services for end-users in terms of the mental status analysis, eating habits monitoring, early prevention of diseases, and other healthcare services. With the cloud-assisted analysis in terms of health and mental status, the analyzing result will be sent to last-mile mobile device of end user, facilitating flexible and personalized interaction.

In summary, the main contributions of this paper include: (1) present various challenging issues to support a rich media interaction between intra-BAN and beyond-BAN; (2) utilize caching and NDN technology to save energy and other resources to distribute rich media contents; (3) propose a novel application of NDN and adaptive streaming to enhance Quality of Service (QoS) of realtime transmission data from WBAN; (4) propose an approach to implement the integrated healthcare system which contains LTE, NDN and adaptive streaming.

The remainder of this paper is organized as follows. In Section 2, we present our network architecture. In Section 3, we introduce the implementation of NDN and adaptive streaming. Section 4 describes our simulation settings and performance metrics. Section 5 presents simulation results and verifies the proposed schemes. Finally, Section 6 concludes this paper.

2. The proposed network architecture

In this section, we first present the problems existing in typical Zigbee network for healthcare. Then, an improved network is proposed to address those problems.

2.1. Existing problems in typical WBAN

In a typical *WBAN* for medical monitoring [6], a certain number of body sensor nodes are often attached to hospitalized patient for continuously monitoring activities and health status. The intelligent wearable sensor node has three main functions, i.e., (i) retrieving environmental and/or physiological sensory data, (ii) local processing, and (iii) data routing. In order to achieve high comfortableness, modern body sensors possess the features of lightweight, small size, and ultra low power, etc. There are many protocols and radio technologies provided for WBAN transmissions, including Bluetooth, Bluetooth Low Energy, Zigbee/IEEE 802.15.4, Ultra-Wide Band (UWB) and IEEE 802.15.6. Among these radio technologies, Zigbee is still the most popular choice for WBAN according to Zigbee Alliance, which is an association of companies working together to develop standard and products for reliable, low bit-rate, low power and cost-effective deployment. In a Zigbee network for healthcare, the body signals of a patient are first collected by several Zigbee-enabled sensors called end-devices, and then transmitted to a master node called Zigbee coordinator. Since only short-range communications are supported between Zigbee end-devices and the coordinator, the following disadvantage exists in a hospital scenario where a physician carries a mobile device to collect patient's data: the mobility of patient and physician is limited to ensure the mobile devices located within the radio range of the Zigbee coordinator. The previous work address various issues including real-time patient monitoring via Zigbee communication [12], but the short distance is usually assumed between body sensors and access points. In order to deliver the body signals to remote terminals in a larger range, the Zigbee coordinator needs to be equipped with another wireless interface. For example, mechanisms are designed to relay Zigbee data to other types of wired or wireless infrastructures to solve the limited coverage problem of Zigbee [13].

2.2. The proposed network with multiple co-existing interfaces

In order to address the issue mentioned in previous section, we propose a solution by seamlessly integrating Zigbee with TCP/IP protocols and equipping the Zigbee coordinator with either LTE or WiFi interface. In such a network where multiple radio interfaces co-exist, radio collision is a critical problem. The key physical parameters of Zigbee, WiFi, and LTE must be considered when determining the effects of radio interference among different kinds of networks. According to the frequency characteristics, there is no radio interference between LTE radio and Zigbee radio but the radio collision will happen if both WiFi and Zigbee uses industry, medicine and science (IMS) band. For this reason, the WiFi devices and access points should be configured in IEEE 802.11a standard while Zigbee networks use 2450 MHz IMS band.

Fig. 3 shows the proposed network architecture. The Zigbee network can be configured in a star, tree or mesh structure depending on application scenario. If patients are required to stay in bed or only allowed to move indoor, all of the three network structures can be used. In case that patients are outdoor with high mobility, a star structure network should be used. However, the peak data rate of the Zigbee network is limited to 250 Kbps, while the throughput is seriously degenerated after multiple hops. Thus, the star structure is used in most cases to achieve maximum data rate. Since star topology is used, the Zigbee gateway only serves one connection at one time, while the other requests should be in the waiting queue. In this case, the NDN technology can be used to reduce upstream data traffic to alleviate the limited bandwidth. Thus, the Zigbee coordinator (also known as a Zigbee gateway) is equipped with the functions of NDN and adaptive streaming in the proposed architecture. If the Zigbee gateway receives *Interest* from user, it will check its content store first. If the cached data is found to satisfy the *Interest*, the data will be forwarded to the user directly. Otherwise, new data will be queried from Zigbee end-devices. In case that the content store is full, the Zigbee gateway uses the *first in first out* (FIFO) replacement policy to remove the oldest data and cache the new data.

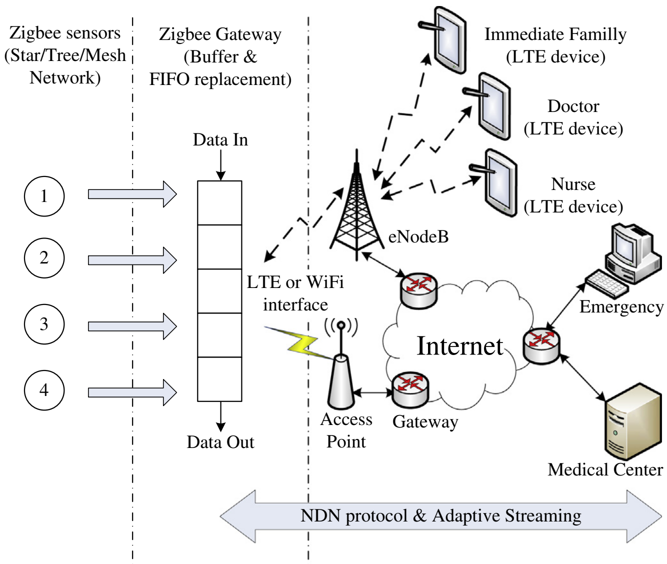


Fig. 3. The proposed architecture of integrated WBAN with LTE networks.

2.3. The integration of Zigbee protocol and TCP/IP protocol

A Zigbee protocol standard includes four layers [4]. (1) The *physical* layer supports functionalities for channel selection, link quality estimation, and channel assessment, etc. (2) The *medium access control* (MAC) layer defines three types of nodes, i.e., coordinator, router or end-device [14,16]. Each personal area network (PAN) only has one coordinator node and it is recognized by an identification number called PAN-ID. Child nodes are known as end-devices or routers needing to have the same PAN-ID as the coordinator. (3) At the *network* layer, the topology of the PAN network is configured. Besides the star topology that naturally maps to the corresponding topology in IEEE 802.15.4, the Zigbee network layer also supports more complex topologies such as tree and a mesh structures [15]. The network layer is in charge of organizing and providing routing over a multi-hop network (built on top of the IEEE 802.15.4 functionalities).

(4) An *application* layer provides a framework for application development. Based on the characteristics of OPNET Zigbee application layer module, we build up an adaptive layer, and implement the seamless integration of Zigbee and TCP/IP protocol. Thus, node model design for the new Zigbee coordinator device is shown in Fig. 4.

3. Efficient content delivery via NDN and adaptive streaming

In this section, we present the implementation of NDN and adaptive streaming in the proposed network architecture. Fig. 5 illustrates the basic idea of efficient content delivery via NDN technology and adaptive streaming.

3.1. Efficient content delivery via named data networking

NDN was first proposed by V. Jacobson in 2009 [11]. Then, various projects and prototypes have been deployed to verify the effectiveness of NDN [1,2,8]. In NDN, each content is identified by a URL-like name, instead of IP address. There are two main types of NDN packets, i.e., interest packet (*Interest*) and data packet (*Data*). To request a content, an *Interest* containing content name is sent towards content provider. Meanwhile, the intermediate nodes forward the *Interest* to the next hop

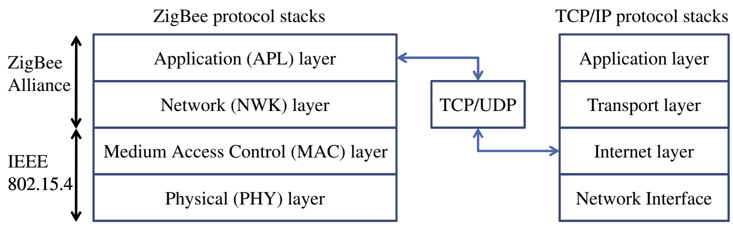


Fig. 4. The seamless integration of Zigbee and TCP/IP protocol.

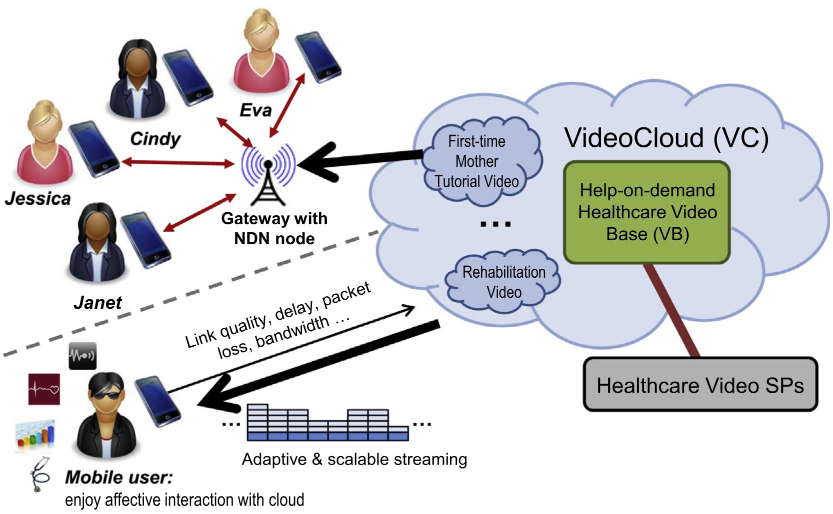


Fig. 5. Illustration of efficient content delivery from cloud via NDN technology and adaptive streaming.

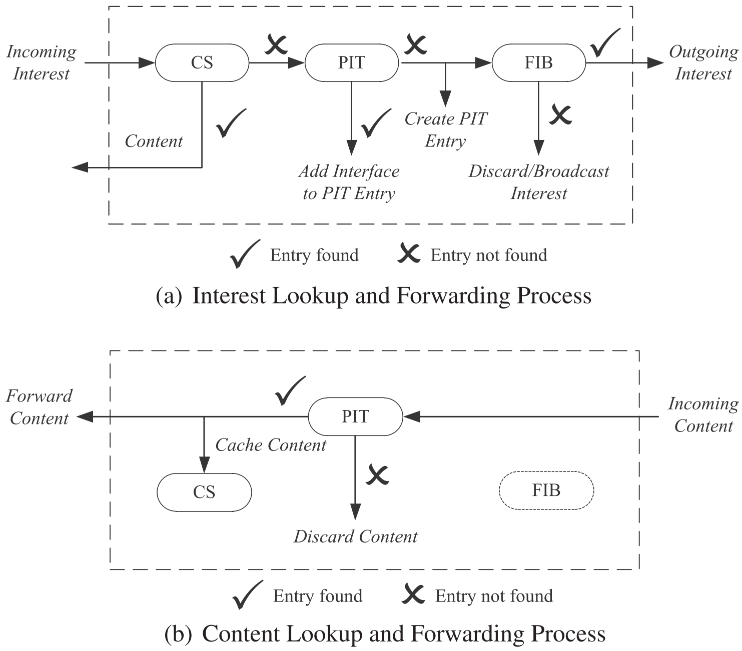


Fig. 6. How NDN works?

closer to the content provider by parsing the name. Once the corresponding *Data* is found either by the content provider or an intermediate node, it is returned to the user launching the *Interest* along the reverse path where *Data* is cached by those nodes it goes through. Here, node (or NDN node) can be server, gateway or router. Each node maintains three data structures: *Forwarding Information Base* (*FIB*), *Pending Interest Table* (*PIT*) and *Content Store* (*CS*). Fig. 6 illustrates the novel routing protocol utilized by NDN. When an *Interest* is forwarded towards *Upstreams* content provider, the following procedure is performed in an intermediate NDN node:

- *Data-matching in content store:* When a node receives an *Interest*, it first performs data-matching process by looking up its *CS* which caches the received contents. If a matched content is found in *CS*, the *Data* will be responded to the incoming interface of the *Interest*.
- *Interest-matching in PIT:* If data-matching fails, the node will check its *PIT*. The *PIT* keeps track on list of those *Interest*s whose users are waiting for the contents. If the *Interest* is identical with one pending interest packet recorded in a *PIT* entry, the incoming interface of the *Interest* will be added to that entry's list of incoming interfaces.
- *Name-prefixes-matching in FIB: FIB* stores name prefixes. Each name prefix may corresponds to multiple outgoing interfaces. If there is matching FIB entry, the *Interest* will be forwarded to the chosen interface(s), and a new *PIT* entry is created.
- *No-matching:* If above three processes fail, the *Interest* will be discarded.

When a *Data* is returned towards *Downstream* NDN node, a longest-match lookup of the content name is performed. If the matching *PIT* entry is found, the *Data* will be distributed to those interfaces where the *Interest* were received. Then, the *PIT* entry is removed while the *Data* is cached in *CS*. Otherwise, the *Data* is discarded and destroyed.

3.2. Adaptive streaming

In case that the quality of network connections fluctuates, the adaptive streaming technique is an efficient approach to decrease packet loss ratio. The end-users can automatically adjust the requested data rate to adapt to the current status of network connection. When Zigbee gateway keeps sending contents with full data transmission rate, the *Interest* sent by the end-user might get lost. Then, the end-user needs to resend the *Interest* packets to request the content. In the example given in Fig. 7, we define three data rate classes: *high, middle and low*, which are decided by the end-user according to the number of re-sent *Interest* packets. According to the status of network connection, the data rate is adapted in order to obtain a better performance in terms of packet loss ratio, as shown in Fig. 7. The pseudo code of the adaptive stream is given in Algorithm 1, where R_D represents data rate.

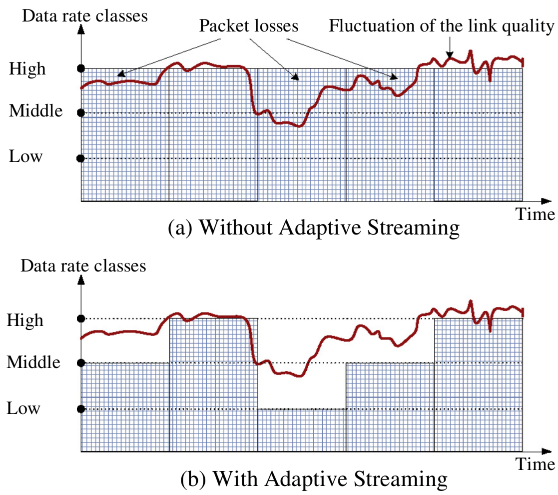


Fig. 7. Illustration of adaptive streaming applied in NDNC-BAN.

Algorithm 1. Adaptive streaming

---

begin
initialization
  $R_D = max\_value$
loop
  Send requested content with data rate of R_D
  if fail to receive content, and it is the second try **then**
    $R_D = median\_value$
    Resend the requested content with data rate of R_D
    if fail to receive content, and it is the first try **then**
      $R_D = min\_value$
      while fail to receive content **do**
        Resend the requested content with data rate of R_D
      end while
    else
      $R_D = median\_value$
    end if
  else
    $R_D = max\_value$
  end if
end loop

---

4. Simulation methodology

To evaluate the performance of the proposed schemes, we compare the following schemes using extensive simulation studies: (i) the scheme with NDN and adaptive streaming (denoted by *NDN-Adapt*); (ii) the scheme with C/S and adaptive streaming (denoted by *CS-Adapt*); and (iii) the scheme with C/S with fixed data rate, (denoted by *CS-Only*). We present our simulation settings and performance metrics in this section. The simulation results are discussed in Section 5.

NDN mechanism and the proposed schemes are implemented and simulated by using the OPNET Modeler[3]. The NDN protocol is implemented in the network-layer, and it can run on top of any available link-layer protocol module. Note, a real NDN system which is designed to replace TCP/IP, is not considered here. Instead, we emphasize that the NDN model is compatible with today's Internet. Thus, the NDN process module is built by OPNET overlays the IP layer. Notation used in this paper is given in Table 1.

4.1. Network model

First, we present our OPNET network model. As shown in Fig. 8, the simulated network includes three subnetworks: LTE network, WiFi network and WAN network. The LTE network covers three cells which are identified by CELL 1, CELL 2 and

Table 1
Notation.

Symbol	Definition
Interest	Interest packet
Data	Data packet
CS	Content store
n_{gw}	The number of Zigbee gateway
n_{user}	The number of end-users
$S_{data}(G_i)$	The size of data sent by the ith Zigbee gateway
$S_{data}(U_i)$	The size of data received by the ith end-user
$T^{\uparrow}_{Interest}$	The time when *Interest* is sent towards content provider
$T^{\downarrow}_{Data}$	The time when *Data* is received
T_{sim}	The time when simulation starts
T_{G_i}	The time when the ith gateway depletes its energy
f_C	Carrier frequency
E_{GW}	Energy level of Zigbee gateway
$E_{con}(G_i)$	Energy consumption of the ith Zigbee gateway
E_I	The communication energy cost to receive *Interest*
E_D	The communication energy cost to reply *Data*
GW^{WiFi}_{Zigbee}	Zigbee gateway with WiFi interface
GW^{LTE}_{Zigbee}	Zigbee gateway with LTE interface
NDN-Adapt	NDN mode with adaptive streaming
CS-Adapt	Client–server mode with adaptive streaming
CS-Only	Client–server mode with fixed data rate

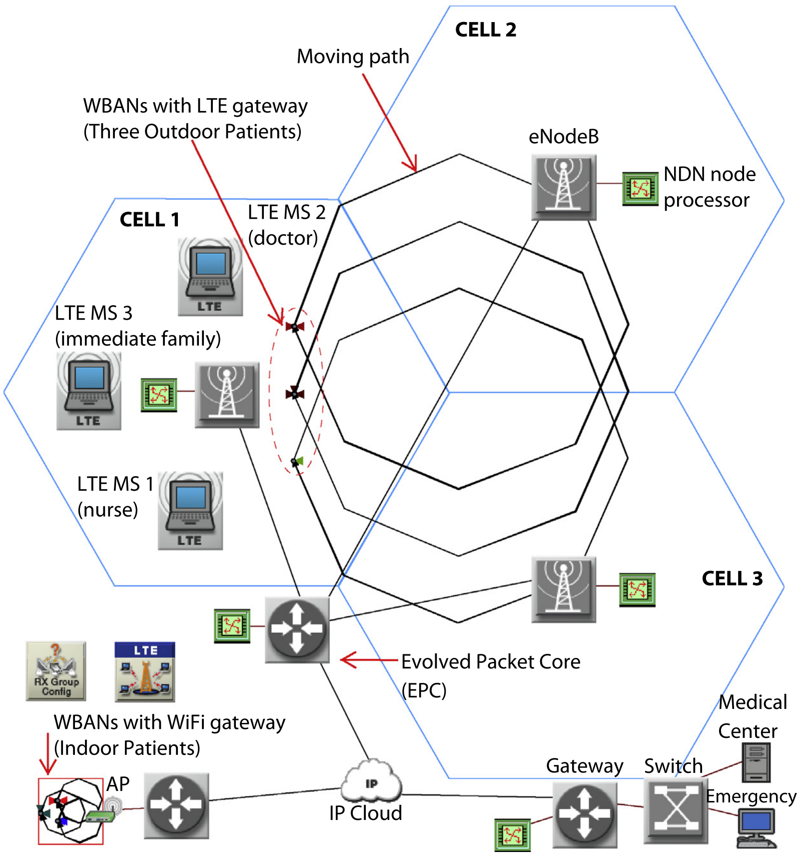


Fig. 8. Network model.

CELL 3, respectively. Three LTE mobile stations (MSs) are analogous to mobile devices carried by a doctor, a nurse and an immediate family member. In the center of Fig. 8, the three circles are analogous to WBANs possessed by three outdoor patients, and each WBAN has a Zigbee gateway with LTE interface (denoted by GW^{LTE}_{Zigbee}). They walk around the region covered by the three LTE cells, which simulates the scenario of patients outdoor movements. The roaming capability between *eNodeBs* enables a WBAN to keep the connections with the doctor, the nurse and the immediate family member. In the lower-left corner of Fig. 8, there are three more WBANs, each of which includes a Zigbee gateway with WiFi interface (denoted by GW^{WiFi}_{Zigbee}). These three WBANs correspond to the three patients moving slowly indoors within the radio range of the WiFi access point. The WAN network represents the IP backbone that connects the LTE network, WiFi network and two servers. In the lower-right corner of the figure, one server distributes the healthcare contents from the medical center while the other one provides emergency medical service.

OPNET Modeler 16.0 is used to implement the NDN protocol over LTE network [5]. Though an open source NDN model named ''NDN-SIM'' has been built up by NS3 [2], it is lack of LTE model and comprehensive mobile network models. By comparison, our NDN model outperforms NDN-SIM in terms of mobile network simulations, e.g., 2.5G/3G/4G, and is more realistic than NDN-SIM.

4.2. NDN Process Module

The NDN process module is specially implemented to realize NDN protocol. It has three data structures: FIB, PIT and CS, which are described in Section 3.1. When the NDN process module is integrated with node models of the other network devices, those devices will have NDN function, as shown in Fig. 9. We integrate the NDN process module into all the network elements involved in our network system, such as: eNodeB, LTE Mobile Station, *Evolved Packet Core* (EPC), Gateway, PC, Server and IP Cloud.

Note that this paper includes two kinds of Zigbee gateways, i.e., GW^{LTE}_{Zigbee} and GW^{WiFi}_{Zigbee}. Here, we take GW^{WiFi}_{Zigbee} as an example. After equipped with a NDN process module, the Zigbee gateway node model is shown in Fig. 10. When the Zigbee end-device forwards upstream traffic, the data is first routed to the application layer of GW^{WiFi}_{Zigbee}, and then processed in the NDN process module. In the NDN process module, there is a buffer memory with a FIFO replacement policy to store all contents from the Zigbee end-devices. When an *Interest* comes to the Zigbee gateway, the destination IP address and the data rate (i.e., R_D) can be obtained from the *Interest*. If requested content exists, the Zigbee gateway responds the *Interest* by sending the content to the destination with the particular R_D from its buffer.

4.3. Energy Model

In a real scenario, the patient usually carries a smart phone as a Zigbee gateway, whose energy is limited. A certain amount of energy will be consumed after various operations in terms of CPU, memory, display and wireless interfaces, etc. Since we just need to compare the energy performance between GW^{LTE}_{Zigbee} and GW^{WiFi}_{Zigbee}, only the difference of energy consumption via LTE or WiFi interface is considered when Zigbee gateway sends or receives packets. Let E_{rp} represent the energy consumption for periodically publishing a root's name every 100 s. Let E_I be the energy consumption for receiving *Interest* packets in a NDN node, while E_D is the energy for replying *Data* packets in a NDN node. Let E_{left} represent the current energy level of a Zigbee gateway. Then, E_{left} is updated according to Eq. (1):

$$E_{left} = E_{left} - (E_{rp} + E_I + E_D) \tag{1}$$

We utilize the measurement results presented in [9], including those reflecting power characteristics of 4G LTE network. Table 2 lists various important parameters for the simulation.

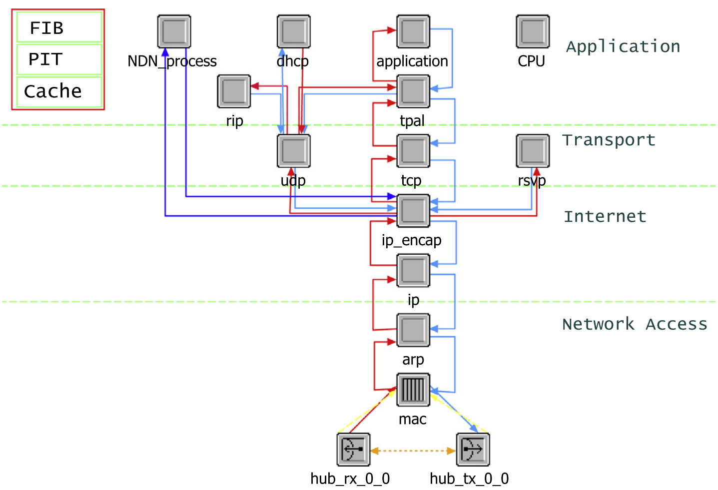


Fig. 9. OPNET node model with NDN process module.

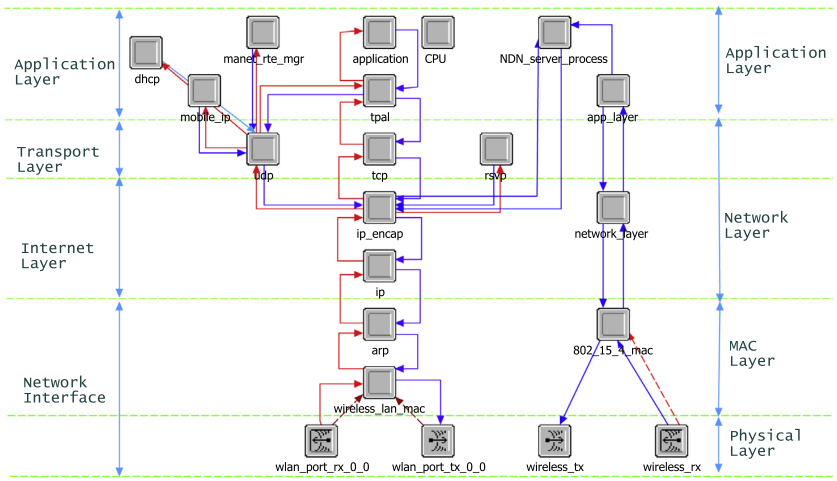


Fig. 10. NDN-enabled Zigbee gateway node model with WiFi interface.

Table 2
Sum up important parameters for the simulation.

Element	Attribute	Value
LTE	Cell diameter	2000 m
	f_C (uplink/downlink)	1920/2110 MHz
	Bandwidth	20 MHz; 3 MHz
	Patient moving speed	20 km/h
	WBANs quality	3
WiFi	Cell diameter	150 m
	Wireless standard	IEEE802.11a
	Patient moving speed	2 km/h
	WBANs quality	3
Zigbee gateway	Cell diameter	2 m
	f_C (uplink/downlink)	2450 MHz
	NDN root	ccnx://epicLAB/wban[i]/
	File size	1 Mb
	Packet size	1024 bits
	Initial energy	2000 J
WAN	Link for server/PC	1000BaseX/100BaseT
LTE MSs/PCs	NDN directory	ccnx://epicLAB/wban[i]/
	Start time	200 + rand (10) s
	Stop time	840 s/infinity
	Interest interval time	3 s
	Data rate classes	1 Mbps/500 Kbps/250 Kbps

4.4. Performance metrics

In this subsection, five performance metrics are introduced.

1. *Average bits sent by Zigbee gateways*: It is denoted by S^{GW}_{data}, which represents average bits sent from a Zigbee gateway. Let $S_{data}(G_i)$ denote the bits sent by the ith gateway. Then, S^{GW}_{data} is equal to:

$$S^{GW}_{data} = \frac{\sum_{i=1}^{n_{gw}} S_{data}(G_i)}{n_{gw}} \tag{2}$$

2. *Average bits received by end users*: It is denoted by R^{U}_{data}. Here, the end users include LTE mobile stations and PCs, as shown in Fig. 3. Let $S_{data}(U_i)$ denote the bits received by the ith end user, while n_{user} denote the number of end users. Then, R^{U}_{data} is calculated by Eq. (3).

$$R^{U}_{data} = \frac{\sum_{i=1}^{n_{user}} S_{data}(U_i)}{n_{user}} \tag{3}$$

3. *Average round trip time* (RTT): It is denoted by RTT. Let $T^{\uparrow}_{Interest}$ and $T^{\downarrow}_{Data}$ denote the time when the interest packet is sent and the time when the data packet is received, respectively. As shown in Eq. (4), the average RTT is equal to:

$$RTT = \frac{\sum_{i=1}^{n_{user}} (T^{\downarrow}_{Data} - T^{\uparrow}_{Interest})}{n_{user}} \tag{4}$$

4. *Average energy consumption in gateways*: It is denoted by E_{GW}, which is measured by the average energy consumption of all the Zigbee gateways, as shown in Eq. (5).

$$E_{GW} = \frac{\sum_{i=1}^{n_{gw}} E_{con}(G_i)}{n_{gw}} \tag{5}$$

5. *Average lifetime of gateways*: It is denoted by L_{GW}, which is used to evaluate the battery life of all the Zigbee gateways, as shown in Eq. (5).

$$L_{GW} = \frac{\sum_{i=1}^{n_{gw}} (T_{G_i} - T_{sim})}{n_{gw}} \tag{6}$$

5. Performance evaluation

In NDN, *Interest* might be immediately satisfied by edge routers or Zigbee gateway. Therefore, in comparison with the pure C/S mode, NDN have three advantages: (i) reduced number of requested contents that need to be fetched to the Zigbee gateway, (ii) lower RTT, and (iii) smaller energy consumption of the Zigbee gateway.

In order to verify above advantages obtained from NDN, we run twice for each scenario with different settings in terms of simulation time. In the first simulation, the time is set to 840 s, and the simulation results are used to calculate S^{GW}_{data} and *RTT*. The second simulation does not stop until Zigbee gateway exhausts its energy, and the results are used to determine E_{GW} and L_{GW}. In order to make a better presentation of our results, we collect and classify all simulation results from OPNET, export them to spreadsheet and use Matlab to illustrate the final results.

5.1. Impact of adaptive streaming and NDN

Due to the channel fluctuation of wireless link, *Interest* may get lost. Then, end users need to resend the *Interest* after its time out. Fig. 11 shows the number of resent interest packets when simulation goes on. If the time-out of *Interest* happens, the resent count is increased by 1, then the data rate is updated according to the resent count and user requirements. After setting the updated data rate in the *Interest*, it will be sent again. As shown in Fig. 11, data rate becomes lower when resent count increases. In our system, adaptive streaming is employed, such that the bit rate is adjusted dynamically and the updated data rate is set in each *Interest*, for adapting the fluctuation of wireless link.

5.1.1. Comparisons of traffic load and throughput

In order to evaluate the impact of adaptive streaming, we compare the performance of different schemes including *NDN-Adapt*, *CS-Adapt* and *CS-Only*, as shown in Fig. 12. In the simulation, we set the bandwidth of LTE to 20 MHz. And only GW^{LTE}_{Zigbee} is investigated in this section, since similar trend can be observed for GW^{WiFi}_{Zigbee}. As shown in Fig. 12(a), S^{GW}_{data} of *CS-Only* is larger than other two schemes employing adaptive streaming. Furthermore, when NDN technique is applied, the traffic load is

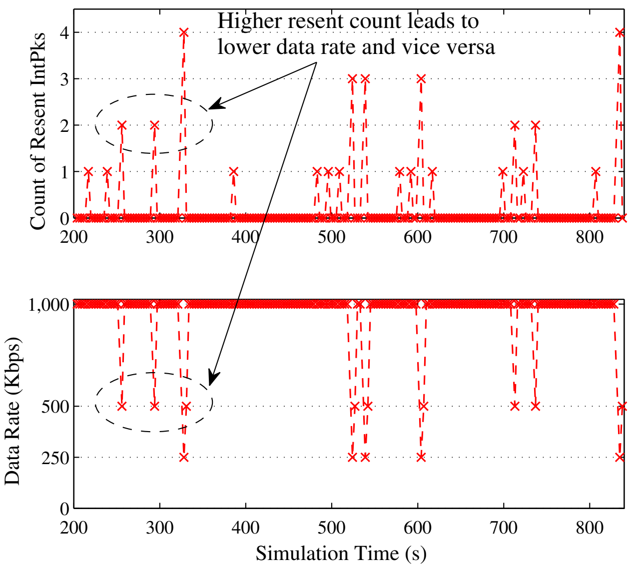
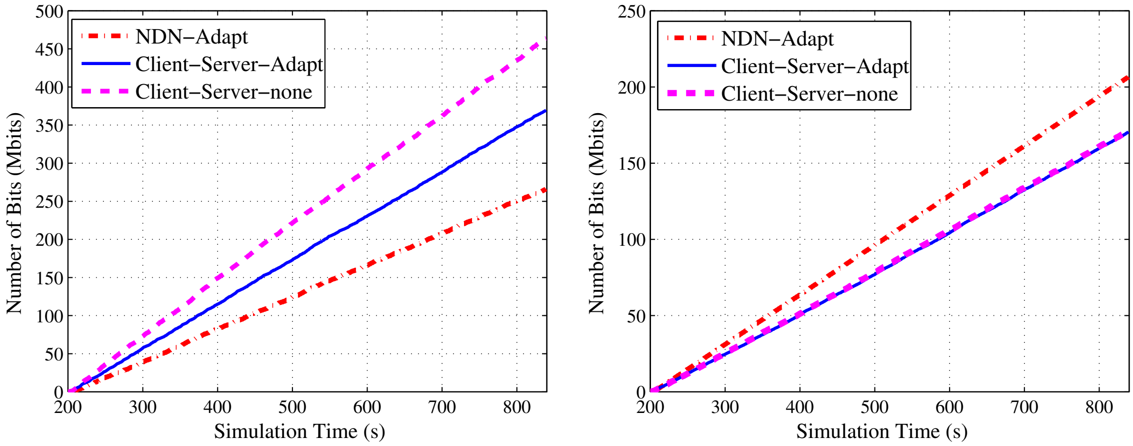


Fig. 11. The relationship between the number of resent *Interest* packets and the practical data rate.



(a) Impact of different schemes on average total bits sent by the Zigbee gateways

(b) Impact of different schemes on average total bits received by the end users

Fig. 12. Comparisons of *NDN-Adapt*, *CS-Adapt* and *CS-Only* in terms of S^{GW}_{data} and R^{U}_{data}.

decreased from 350 Mbits to 250 Mbits when simulation time reaches 800 s. As mentioned, the important design rationale is to save energy of GW^{LTE}_{Zigbee} and GW^{WiFi}_{Zigbee} as much as possible. Thus, *NDN-Adapt* exhibits the best performance with lowest bits sent from the gateways while meeting the QoS requirements.

Fig. 12(b) shows the average amount of bits received in the end users. In *NDN-Adapt*, the end users get highest QoE since its S^{U}_{data} is higher than *CS-Adapt* and *CS-Only*. As shown in Figs. 12(a) and (b), the following observations can be obtained:

- In NDN, an *Interest* from end user will be satisfied with a certain probability before it reaches to a Zigbee gateway, and the number of *Data* sent by the Zigbee gateway is reduced. By comparison, when C/S mode is employed, the Zigbee gateway always needs to reply respond *Interest* from end-user.
- Due to limited capacity of a Zigbee gateway, the delivery of *Data* may fail, which causes the failure of end-user to receive complete content. In such case, end user needs to resend an *Interest* to the Zigbee gateway.
- Adaptive streaming plays an important role for adjusting data rate to a suitable value, in order to alleviate the network congestion.

5.1.2. Comparisons of RTT

Fig. 13 shows the comparison of RTT performance. In the *NDN-Adapt* scheme, the RTT is most stable and below 0.25 s. In the *CS-Adapt* scheme, the RTT is unstable but still lower than 1 s. However, the RTT of *CS-Only* fluctuates between 0.5 s and 4 s, which illustrates that the adoption of adaptive streaming exhibits impressive advantage in terms of delay performance.

5.1.3. Comparisons of gateway lifetime

Fig. 14 shows the comparison of L_{GW}. With simulation going on, the energy level of gateway continuously decreases until it is depleted. Among the three compared schemes, average gateway lifetime in *NDN-Adapt* scheme always outperforms the

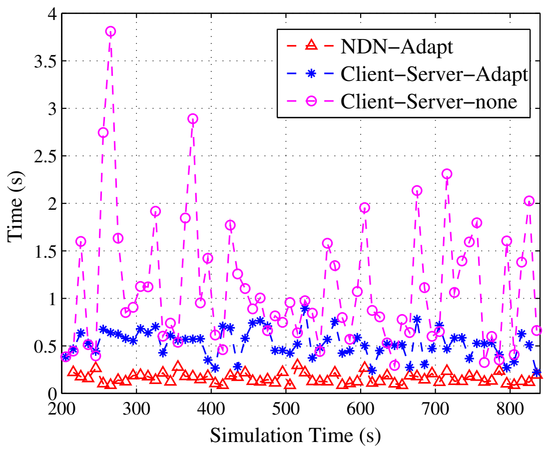


Fig. 13. Impact of adaptive streaming and NDN on average RTT.

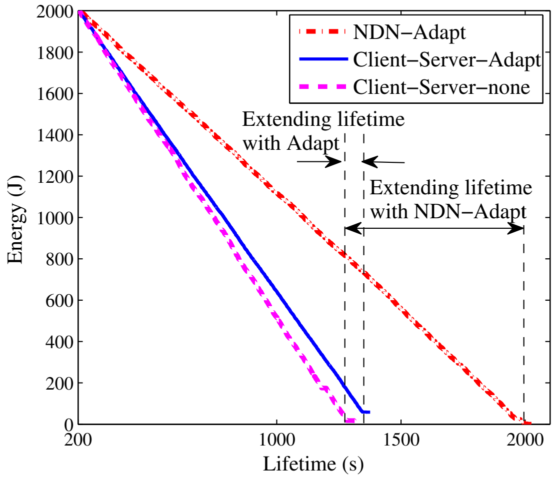


Fig. 14. Impact of adaptive streaming and NDN on average gateway lifetime.

others. It is because the total bits sent by the Zigbee gateway is saved extensively by the adoption of NDN, as shown in Fig. 12(a). Thus, NDN can extend lifetime for Zigbee gateway significantly by offloading traffic, minimizing total bits sent and reducing RTT. The introduction of adaptive streaming also favors the extension of lifetime.

5.2. Performance comparison under various Zigbee gateways with LTE or WiFi interfaces

We fix the scheme to *NDN-Adapt* while varying different interfaces for Zigbee gateway, and compare various performance in terms of S_{data}^{GW}, RTT, and L_{GW}.

5.2.1. Comparisons of average bits sent by the Zigbee gateways

In Fig. 15, average total bits sent by GW_{Zigbee}^{LTE} are higher than GW_{Zigbee}^{WiFi} for the following reasons:

- Since star topology is used, the transmission link to Zigbee gateway becomes the bottleneck in the network. Compared to the LTE scenario, the transmission bottleneck problem in WiFi scenario is more serious. With regard to WiFi, all stations share the same physical channel and the WiFi access point provides services to all stations with the *first in first serve* (FIFS) policy.
- In the LTE scenario, all stations can access different time slots, facilitating data delivery in parallel. Thus, the LTE network outperforms the WiFi network in terms of QoS provisioning.

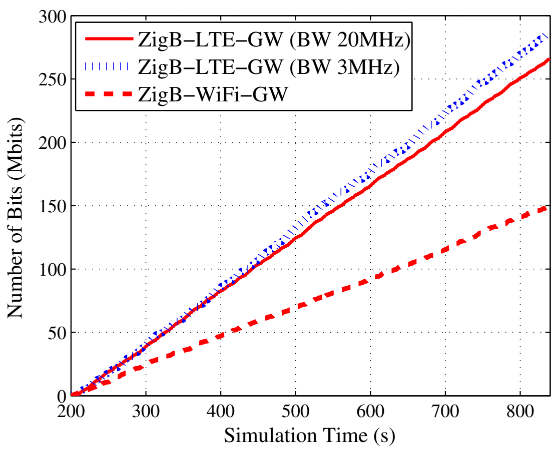


Fig. 15. Performance comparison under various Zigbee gateways with LTE or WiFi interfaces in terms of S_{data}^{GW}.

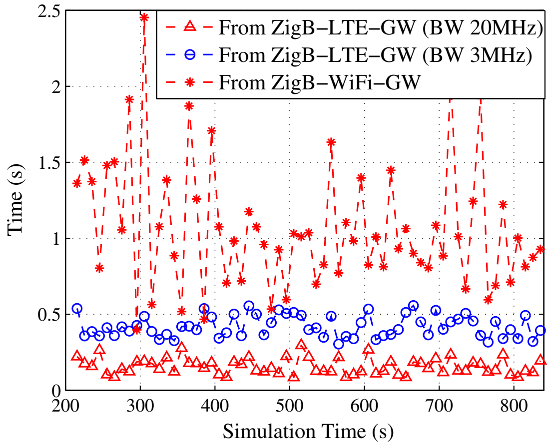


Fig. 16. Performance comparison under various Zigbee gateways with LTE or WiFi interfaces in terms of average RTT.

5.2.2. Comparisons of RTT

In Fig. 16, we compare the RTT performance among three types of Zigbee gateways:

1. In the scenario employing GW_{Zigbee}^{LTE} with 20 MHz bandwidth, the peak data rates for uplink and downlink are 75 and 300 Mbps, respectively, while the RTT is stable and below 0.25 s.
2. In the scenario employing GW_{Zigbee}^{LTE} with 3 MHz bandwidth, the peak data rate is 25/50 Mbps and the RTT is always below 0.5 s.
3. In the scenario employing GW_{Zigbee}^{WiFi} with 802.11a, the peak data rate is 54 Mbps, and the RTT fluctuates between 0.5 and 2.5 s.

5.2.3. Comparisons of energy consumption and lifetime

In Fig. 17, it illustrates that the battery of GW_{Zigbee}^{LTE} is consumed more quickly and the lifetime is around 75% shorter than that of GW_{Zigbee}^{WiFi} because of the following reasons:

- In Fig. 15, total bits sent of GW_{Zigbee}^{LTE} are much higher than GW_{Zigbee}^{WiFi}.
- Because of some key differences between LTE link and WiFi link, such as radio transmission range, peak data bit rate, and radio resource control, etc., the energy consumption of per bit transmission in LTE is higher than WiFi.

Based on the above simulation results, GW_{Zigbee}^{LTE} is the best choice for QoS support in the healthcare system. However, the cost for the LTE device is higher than the WiFi device. Thus, the trade-off between the cost and the QoS provisioning should be considered carefully when designing specific healthcare applications.

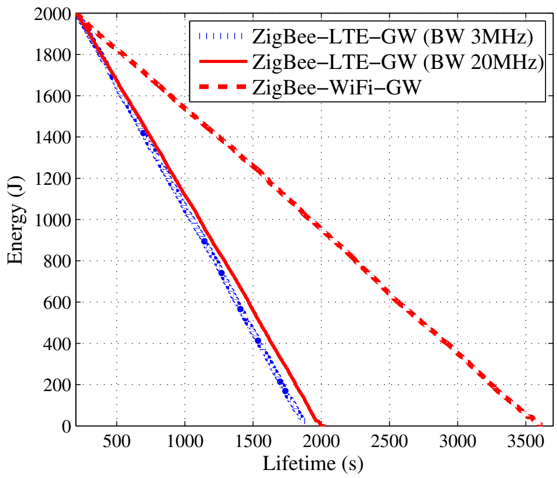


Fig. 17. Performance comparison under various Zigbee gateways with LTE or WiFi interfaces in terms of average lifetime.

6. Conclusion

This paper proposes a novel hybrid WBAN network architecture via NDN and adaptive streaming for remote health monitoring and QoS provisioning. To the best of our knowledge, there are no other research investigating the overlay of NDN on top of WBAN until now. In a dynamic and unstable wireless environment, NDN with adaptive streaming is a suitable solution to support the mobility of both patients and physicians. The simulation results have verified that the contents from WBANs can be transmitted to multiple users smoothly via NDN technology. In summary, while NDN leverages the capacity of the coordinator by edge router caching, adaptive streaming decreases the probability of packets loss by considering dynamic wireless link conditions. The simulated results conducted by OPNET Modeler shows that our solutions improve QoS provisioning for WBAN transmissions significantly. The simulation results also verify that NDN and adaptive streaming are viable approaches for existing challenges in terms of real-time data transmissions between WBAN and beyond-BAN.

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