Architectural Design and Optimization of IPv6-Based Sensor Protocols for Wireless Personal Area Networks

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Abstract: This paper proposes the architecture of light-weight IPv6 (LWIPv6) for low-power wireless personal area networks (LoWPANs), optimize the functions of the architecture's protocols, and reports typical results from the power consumption simulation for LWIPv6. The LoWPAN architecture is oriented to a simple and low-cost wireless communication system, which allows wireless connectivity in a variety of applications with requirements of limited power and relaxed throughput. LoWPAN devices conform to the IEEE 802.15.4 standard specified by the IEEE Standards Society. This paper describes systems requirements analysis (SRA) of LoWPANs with regard to the Internet protocol (IP) layer, the architecture of LWIPv6, and its optimization and performance analysis. The proposed architecture and its protocols in LWIPv6 are substantially optimized for the IP stack, such as header compression, simplified neighbor discovery, and reduction of overhead in the Internet control message protocol (ICMP) functionality. The computer simulation of the proposed architecture is also implemented in the viewpoint of power consumption depending on neigh cache size.

1. Introduction

This paper describes streamlined architecture and design of LWIPv6 to benefit ubiquitous sensor networking (USN) environment. In the public and private areas, a variety of newly emerging business from USN facilitates a multitude of civilian application and service scenarios, such as environment and habitat monitoring, healthcare applications, home automation, consumer electronics, and traffic control as well as military surveillance. It eventually is leading to an advanced ubiquitous society. Systems requirements analysis (SRA) has been performed to design LWIPv6. The SRA is based on the analysis of technical documents of IETF 6LoWPAN working group (WG) and IEEE 802.15.4 WG for IP layer and the PHY/MAC layer, respectively. The design of the LWIPv6 architecture and its implementation has been optimized to suit state-of-the-art wireless sensor hardware platforms such as Mica2 and the Berkeley Mote. This paper is organized as follows: Section 2 describes architecture of LWIPv6, design principles of LWIPv6 protocols, and protocol optimization in LWIPv6. Section 3 lists its benefits in sensor networks and Section 4 shows simulation results. Section 5 concludes the paper.

2. Design of LWIPv6 architecture and Protocols

To make feasible for USN environment, LWIPv6 is designed to achieve three basic goals [1]-[2]: (1) to reduce consumption of electric power, (2) to minimize processing overhead, and (3) to optimize existing protocol functions for less memory use. In order to achieve these goals, LWIPv6 categorizes all functions of IPv6 protocols, and removes all kinds of unnecessary functions for sensor network environment [3]-[6]. The selected functions for sensor networks have been optimized to fit in our design goals of the architecture and configuration of LWIPv6 components are given in Figure 1.

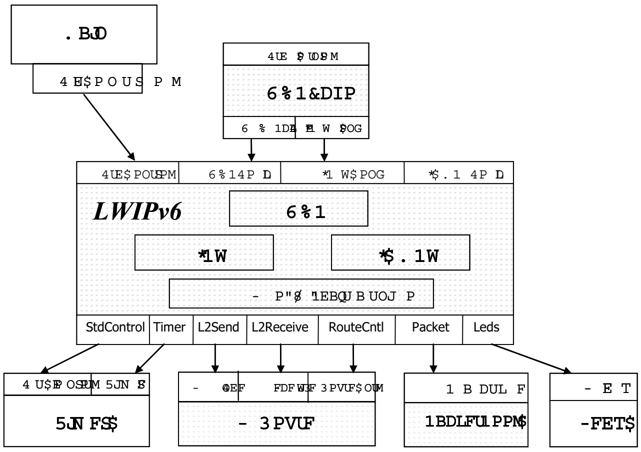

Figure 1: The proposed light-weighted Internet Protocol version 6 (LWIPv6) component configurations.

2. 1 Design Principles of LWIPv6 Sensor Protocols

LWIPv6 is an IPv6-based protocol optimized for sensor network environments, and is designed to exclusively concentrate on basic protocol functionality. The detailed design conditions of LWIPv6 are described as follows:

- Without considering IPv6 router functions of sensor networks, LWIPv6 supports the general IPv6 host functions only. A sensor network, as judged from the standpoint of IPv6, can be thought as a subnet of the IPv6 network. Therefore, the IPv6 router becomes a sink node in the sensor network. A sink node as a gateway in the sensor network is generally provided with a stable supply of electricity, and the node system takes the role of an IPv6 router.

- LWIPv6 does not support multiple interfaces. LWIPv6 is designed to support host functions for sensor nodes. As a host node, sensor node usually does not have more than two network interfaces.
- LWIPv6 does not support multicast and anycast transmission functions. IEEE 802.15.4 specification does not support multicast, and multicast transmission is not suitable for sensor networks as it heavily consumes electricity and entails traffic.
- LWIPv6 does not support additional protocol functions such as Mobile IPv6 and IPSec. In order to optimize, it needs to eliminate functions related to mobile expansion header for supporting Mobile IPv6, and AH (Authentication Header) ESP header for IPSec [7].

2. 2 Configuration of LWIPv6 Sensor Protocols

Table 1 shows a hierarchical configuration of the LWIPv6 protocol. As shown in Table 1, the LWIPv6 protocol supports only UDP in the transport layer. Currently, TCP header compression is not yet supported in the IETF 6LoWPAN adaptation layer. Because the characteristics of sensor networks match the vertical communication method of UDP, LWIPv6 currently supports only UDP in the transport layer. LWIPv6 is however expected to support the TCP protocol as a TCP header compression method of the IETF 6LoWPAN, and is eventually expected to become an international standard in the near future, and the studies on optimizing TCP protocol will further progress. For the header compression of the LWIPv6 protocols, the 6LoWPAN adaptation layer of the IETF 6LoWPAN WG has been applied.

Table 1: Hierarchical protocol configuration.

Hierarchies	Protocols supported
Transport hierarchy	UDP
Network hierarchy	IPv6, ICMPv6
Adaptation hierarchy	6LoWPAN Adaptation Layer
Data-Link/PHY hierarchy	Multi-Hop Routing, IEEE 802.15.4

2. 3 Application of Adaptation Layer of LWIPv6 Sensor Protocols and Multi-Hop Routing

Research efforts of multi-hop routing algorithms have been made for many years [8]. Most related work focuses on optimizing multi-hop routing for specific sensor application scenarios.LWIPv6 supports three multi-hop routing protocols among well-known protocols: Flooding, MutiHopLQI and TinyAODV. One of those three protocols can be selected for the purpose of the applications. Table 2 shows routing protocols which LWIPv6 supports. Flooding broadcast packets to all connected nodes in the network. This is the simplest way to make multi-hop routing, but not suitable for busy traffic network. MultiHopLQI is the routing protocol between the representative sensor nodes in the source program of TinyOS, and the sink, or the sensor gateway. In this routing protocol, a node chooses its neighboring nodes based on the minimum hop count. When the node forwards packets, it chooses the most signal-sensitive node among its neighbor nodes, by checking their LQI (Link Quality Indicator). LWIPv6 support this protocol as optional function. TinyAODV is an on-demand multi-hop routing protocol which runs on TinyOS by simplifying the existing AODV (Ad-hoc On Demand Vector) routing protocol.

Table 2: LWIPv6 multi-hop routing.

Protocol	Functions	Classification
Multi-Hop Routing	Flooding	
	MultiHopLQI	Option
	TinyAODV	
Adaptation Layer	Header Compression and Fragmentation	Option

For the multi-hop routing, the IETF 6LoWPAN adaptation layer has been left as an option so that the users can choose according to the environment. While the compression and fragmentation of the packet header are inevitably needed because of the small size of the IEEE 802.15.4, it may be more effective not to use the adaptation layer if the frequency of packet occurrences is very low, and the amount of the data transaction in the application is negligible. The header may make the overheads occur, but, on the contrary, overhead caused by the compression and the transformation of the packet can be decreased as there is no need to transform IPv6 itself in the 6LoWPAN gateway. Multi-hop routing in sensor network is an important topic for wide-deployment of USN applications. From this analysis and study, it is aware that the current protocols which LWIPv6 supports are not efficiently enough for the sensor network. No matter in which type of sensor network, saving energy is crucially important to devices that are not main-powered but have to rely on a depleting source, such as a battery. Radio communications is a very dominant factor of power consumption. Therefore, the optimization of multi-hop routing protocols is very crucial for battery-powered sensor nodes and the network as a whole. Achieving a minimal number of control messages is a key factor to design routing protocols for sensor networks. Routing overhead must be minimized, as well. LWIPv6 is designed with flexibility, and any new routing protocols are easily able to be ported into LWIPv6. It will support other routing protocols if a standard protocol has been designed, or if a routing protocol is verified to give good performance for sensor networks.

2. 4 Optimization of LWIPv6 Sensor Protocols

Many problems need to be solved in order to apply an IPv6 based protocol stack to sensor networks in fields of practical applications. It is true that a sensor related hardware has been enhanced more and more. However, still the study of a light-weight IPv6-based protocol is essentially remained, because it consumes excessive resource to load IPv6 on a low-cost, low-power and micro-sized sensor node, connected to a low bandwidth wireless sensor network. Therefore, in the LWIPv6, all kinds of unnecessary functions of IPv6 protocols are eliminated, and all properties of sensor networks that could cause large overhead are optimized. Especially, LWIPv6 proposes optimized IPv6 Neighbor Discovery (ND) for sensor networks. IPv6 ND can generate excessive broadcast traffic into sensor networks. The optimization which is proposed in LWIPv6 is required to reduce overhead of running ND function in sensor network environments [9]-[10]. Table 3, 4, 5, and 6 show all kinds of optimization of functions of LWIPv6.

Table 3: Optimizing the IPv6 protocol of LWIPv6.

Protocol	Functions	Classification
IPv6	Routing and Routing Table managing	Remove
	Fragmentation/Reassembly handling	Support
	All the expansion header creations and receptions	Remove

Table 4: Optimizing ICMP functions of LWIPv6.

Protocol	Kinds	Functions	Classification
ICMPv6	Error reporting	Generating and receiving Destination unreachable	Support
		Generating and receiving Time exceeded	Support
		Other error messages	Delete
	Query	Generating and receiving Echo Request/Reply	Support
		Generating and receiving Group Membership message	Delete
		Neighbor Solicitation(NS)/Advertiseme nt(NA)	See Table 6
		Router Solicitation(RS)/Advertiseme nt(RA)	See Table 6

Table 5: Protocol optimization of the LWIPv6 UDP.

Protocol	Protocol supported	Classification
	Generating UDP Checksum	Option
	Receiving and Handling of UDP Checksum	Option

Table 6: Optimizing neighbor discovery function of LWIPv6.

Protocol	Function	Classification
ICMPv6 Neighbor Discovery	RA receptions and Address Auto-configuration by RA	Support
	Duplication Address Detection	Delete
	Address Resolution	Delete
	RS transmission	Optimize
	RA transmission (router only)	Optimize
	Neighbor Cache management	Delete
	Neighbor Unreachability Detection	Delete
	Default Router list and Prefix list management	Delete
	Router Timer and Prefix Timer management	Delete

3. Design and Optimization Results from LWIPv6 Sensor Protocols

According to the architecture and its design principles described in Section 2, LWIPv6 is implemented in the nesC programming environment of TinyOS as shown in Figure 2, and has properties that are optimized for USN, as follows:

- LWIPv6 is implemented to remove unnecessary overheads such as "Buffer Copy" which is not needed by parent application. LWIPv6 is equipped with a function that the data fields in transmission packets are directly sent to upper users. By utilizing this function, the overhead of data copy between application buffer and protocol buffer, which general communication protocols usually have, could be removed.
- LWIPv6 utilizes IPv6 and UDP header compression techniques of IETF 6LoWPAN. The IETF 6LoWPAN adaptation function explained in Section 2 is built in LWIPv6. Users can configure packet header compression functions through the LWIPv6 application.
- In order to support multi-hop transmission of sensor networks, LWIPv6 supports three routing protocols of L2 layer: Flooding, TinyAODV, and MultiHopLQI. Hence, an appropriate multi-hop routing protocol can be selected according to the transmission configuration.

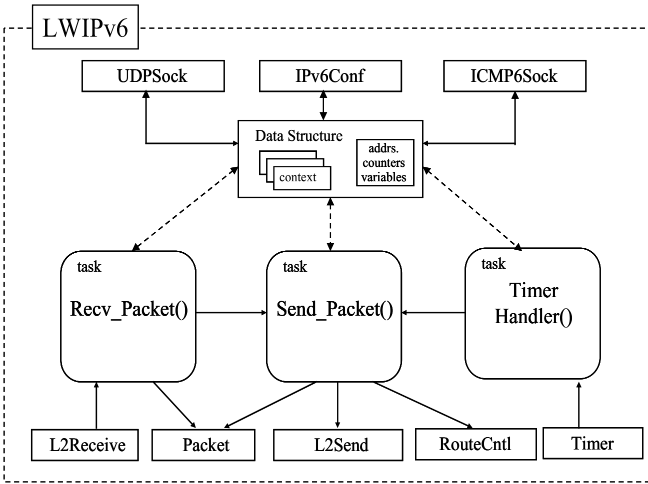

Figure 2: The schematic of the organization of LWIPv6 operation.

4. Simulation Results

The TinyOS Simulator, TOSSIM together with TinyViz and PowerSSIM is used to test the performance of LWIPv6. TOSSIM is a simulator which makes use of discrete events. TOSSIM provides an emulator that runs sensor nodes' programs on development systems (PC), and a simulator which creates virtual environment with various sensor networks. TOSSIM itself is a command-based simulator, but a GUI-based tool called TinyViz which is connected with TOSSIM simulator to provide functions such as setting number/layout of nodes, setting radio link range, applying radio model, various debugging messages, link status, power consumption status (by linking with PowerSSIM), output, etc. PowerSSIM simulates power consumption based on amount on current measured from CPU, Radio, LED, ADC, Sensor, and so on. Figure 3 is an example of Power Profiling output done by applying PowerSSIM to TinyViz. Test results of various application programs of TinyOS shows that direct measurement and PowerSSIM calculation of power consumption displayed less than 5% difference on average. Table 7 and 8 show a power consumption model of Mica2 platform defined by PowerSSIM and simulation parameters.

Figure 4 and 5 shows the simulation results of LWIPv6. Two LOWPAN devices porting LWIPv6 are connected to test power consumption for communication. The graphs indicate that the employment benefit of LWIPv6 as opposed to the conventional IPv6 on LoWPAN devices. LWIPv6 can significantly increase the average lifetime of individual sensor device.

Table 7: Power consumption model of Mica2 platform defined by PowerSSIM.

Mode	Current	Mode	Current
CPU		Radio	
Active	8.0mA	Rx	7.0mA
Idle	3.2mA	Tx(-20dBm)	3.7mA
ADC Noise Reduce	1.0mA	Tx(-19dBm)	5.2mA
Power down	103uA	Tx(-15dBm)	5.4mA
Power save	110uA	Tx(-8dBm)	6.5mA
Standby	216uA	Tx(-5dBm)	7.1mA
Extended standby	223uA	Tx(0dBm)	8.5mA
Internal Oscillator	0.93mA	Tx(+4dBm)	11.6mA
LEDs	2.2mA	Tx(+6dBm)	13.8mA
Sensor board	0.7mA	Tx(+8dBm)	17.4mA
EEPROM access		Tx(+10dBm)	21.5mA
Read	6.2mA		
Read time	565us		
Write	18.4mA		
Write time	12.9us		

Table 8: Simulation parameters.

Parameter	Value	Parameter	Value
Network size	50X50	Radio Model	Lossy
Number of nodes	40	Effective Radio Range	10
Tx Rate	38.4 Kbps	Tx Power(=80)	+6dBm

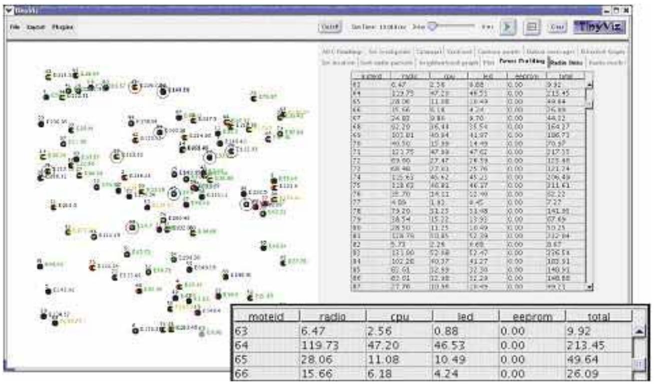

Figure 3: The screen shot of example of power consumption simulation on TinyViz.

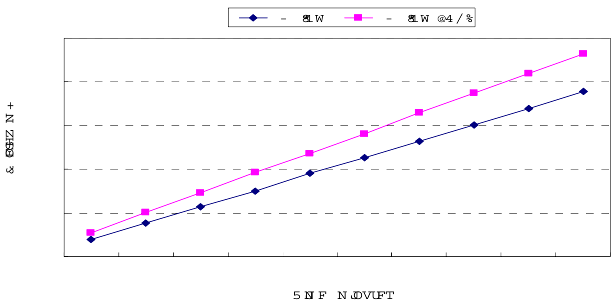

Figure 4: The graph of node's power consumption when LWIPv6 and LWIPv6_SND are applied.

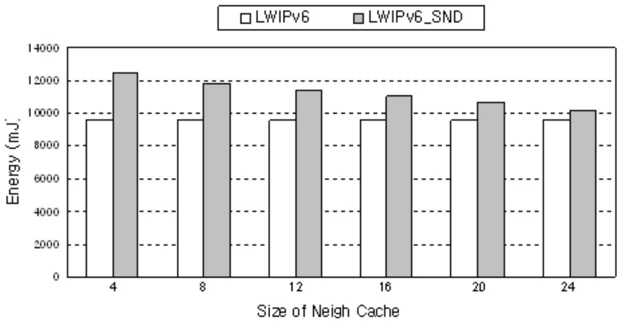

Figure 5: Comparison of the power consumption of LWIPv6 SND depending on neigh cache size.

5. Conclusion

This paper explained the design of LWIPv6 architecture performed by systems requirements analysis (SRA) of LoWPANs to apply Internet protocol (IP) layer. LWIPv6 is desgined to reduce consumption of electric power, to minimize processing overhead, and to optimize existing protocol functions for less memory use. By optimized IPv6 related protocol functions, the implemetation and simulation results shows the efficiency of LWIPv6 on LOWPAN devices. Further studies are on going to enhance LWIPv6 including multi-hop routing for LOWPAN devices.

References

[1] Izuhara, "Specification of TinyIPv6 Protocol Stack for Remote Control and Implementation on FPGA," IPSJ 2002.

[2] Rendon, "Minimum Requirement of IPv6 for Low Cost Network Appliance," INTAP 2002.

[3] Dunkels, "Full TCP/IP for 8bit Architecture," ACM Mobisys 2003.

[4] Dunkels, "Design and Implementation of the lwIP TCP/IP stack," Swedish Institute of Computer Science, February 2001.

[5] Dunkels, "The uIP Embedded TCP/IP Stack: The uIP 1,0 Reference Manual," Swedish Institute of Computer Science, June 2006.

[6] Shelby, Machonen, Riihijarvi, Raivio and Huuskonen, "NanoIP: The Zen of Embedded Networking," ICC 2003.

[7] Gothberg, "Micro-IP for embedded systems," draft-gothberg-micro-ip-00-15.txt, October 2005.

[8] Royer and Toh, "A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks", IEEE Personal Communications, April 1999.

[9] Narten, Nordmark, and Simpson, "Neighbor Discovery for IP version 6 (IPv6)," IETF RFC 2461, December 1998.

[10] Chakrabartic and Nordmark "LowPan Neighbor Discovery Extensions," draft-chakrabarti-lowpan-ipv6-nd-00, July 2005.

***As a visiting research scientist, the corresponding author has been working with the Department of Computer Science at the University of Virginia since August 2007.**