Seamlessly Interconnecting Legacy IEEE 1394 Devices over WiMedia UWB Network: The Mirroring Bridge

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Abstract — Bridging IEEE 1394 buses is becoming important since it can be used to provide wireless connectivity among 1394 devices. Unfortunately, existing bridge mechanisms, such as the IEEE 1394.1 bridge and the transparent bridge, have practical limitations. The former does not support interoperability with legacy 1394 devices and the latter requires a new hardware chipset for bridge implementation. We thus propose a new bridge mechanism called a mirroring bridge to overcome these limitations. It supports interoperability with legacy 1394 devices by emulating remote nodes inside a bridge and via packet address translation that can be implemented through software. We have implemented the proposed bridge mechanism and have succeeded in interconnecting legacy 1394 devices over an experimental WiMedia UWB network. The experimental result showed that the average throughput of the mirroring bridge is 188.7 Mbps, which is 94.4% of the maximum throughput of the UWB chipset used.1

Index Terms — 1394, FireWire, bridging, mirroring bridge, wireless, UWB, WiMedia

I. INTRODUCTION

The IEEE 1394 bus [1] has become the de facto standard for wiring high-speed AV devices in a home network environment. For instance, almost all digital camcorders on the market support 1394 interfaces. Such widespread use of the 1394 bus is due to its distinctive features, such as high bandwidth, plug-and-play and QoS guarantee.

As the home network market is rapidly switching to the wireless domain, the demand for wireless connectivity among 1394 devices is also greatly increasing. In response to this, Wireless Firewire was proposed by The 1394 Trade Association in 2004 [2]. It enables the 1394 protocol to operate over the IEEE 802.15.3 High Rate Wireless Personal Area Network (HR-WPAN) [3] while its programming interface remains intact [4]. Unfortunately, Wireless Firewire has a limited applicability in that it can only be applied to newly developed 1394 devices since it requires that the PHY and LINK layers be modified from the original 1394 standard.

Another viable and practical way to support wireless connectivity among 1394 devices is to use bridges. Bridging is a well known technique for transparently interconnecting different types of network segments in the data link layer [5]. Using this technique, one can achieve wireless connectivity as follows. First, 1394 devices in proximity are wired and thus form a separate 1394 network segment. Then, multiple network segments are linked via a wireless network. In each 1394 network segment, there is a bridge device that serves as a gateway to the wireless network. It performs protocol conversion and address translation between a 1394 network segment and the wireless network.

Up until now, there have been two bridge mechanisms for 1394 devices: the IEEE 1394.1 bridge [6] and the transparent bridge of Philips [7]. Unfortunately, they also possess practical limitations. The former loses interoperability with legacy 1394 devices since it requires nontrivial modifications to the PHY and LINK layers of the original 1394 standard. The latter supports the desired interoperability but requires a new custom hardware chipset for the implementation of a bridge device.

In this paper, we propose a new bridge mechanism to address these limitations. We call it a mirroring bridge. It employs two techniques. First, in a local 1394 network segment, our bridge device emulates all the other 1394 devices in remote network segments. Thus, a local 1394 device can access remote 1394 devices as if they were directly connected by the same network segment. This guarantees interoperability with legacy 1394 devices. Second, our bridge device performs address mapping so that it can assign arbitrary addresses to virtual devices that emulate remote 1394 devices. It is necessary to support arbitrary address assignment in order to maintain compatibility with the self-ID process of the original 1394 standard. To perform the above address mapping, our bridge device maintains a mapping table and translates packet addresses using this table. Since this mechanism can be implemented entirely through software, our mirroring bridge can be constructed with an existing 1394 chipset.

We have implemented the proposed bridge mechanism in our bridge devices and used them to interconnect legacy 1394 devices via a WiMedia UWB network [8], [9]. A bridge

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device is equipped with a 400-MHz PowerPC processor, 1394 interface cards and a WiMedia UWB interface card. Linux version 2.6.18 was used as the operating system and all of the bridging functionalities were implemented as three kernel modules. Using the bridge devices, we constructed a wireless network of nine legacy 1394 devices including HDTVs, digital camcorders, hard disk drives and set-top boxes. We performed a series of experiments to measure the performance of the wireless 1394 network. The average throughput of the network was 188.7 Mbps, which is 94.4% of the maximum throughput of the UWB chipset used. In addition, the average round-trip time of a packet measured 2.154 ms. Since the timeout of the round-trip time is set to 100 ms in the 1394 protocol, our mechanism does not cause multiple retransmissions of a packet that has been correctly received.

The remainder of this paper is organized as follows. In Section II, we give an overview of the 1394 protocol and then model the bridging problem as an address translation problem. In Section III, the existing two bridge mechanisms are reformulated with our address translation function so that their practical limitations can be easily understood. In Section IV, we introduce the key idea behind the mirroring bridge mechanism and show the packet handling process in the mechanism. Section V explains the architectural design of the bridge device. Section VI provides the results of an empirical evaluation of our mechanism in the experimental network. Finally, Section VII serves as our conclusion.

II. Modeling the 1394 Bridging Problem

To aid in understanding the rest of this paper, we first give an overview of the 1394 protocol and define the terms that are used throughout the paper. We then model the bridging problem as an address mapping problem. In doing so, we provide the logical and physical models of the target wireless 1394 network and formulate an address mapping function from the two models.

A. Overview of IEEE 1394 Protocol

Fig. 1 shows the key elements of the 1394 protocol and the relationships among them. In this figure, a node denotes a distinguishable device that has a unique address called a node ID. A node has one or more sockets called ports. Two nodes can be directly connected with each other through a pair of ports using a cable. The nodes and cables physically form a tree topology. The network of cables can be considered a single bus since the ports internally act as repeaters. This bus is represented as a shaded square behind the cables in Fig. 1.

The maximum number of nodes that can be connected via a single 1394 bus is 63 because the size of the node ID is 6 bits and node ID 63 is reserved for a broadcast address [1].

A node is assigned a node ID via a distributed process called the self-ID process. This process is automatically performed by the 1394 chipset when the bus is initialized and a device is plugged in or out. Node IDs are assigned to nodes according to the tree topology of the bus. Thus, it is not possible to program a node with a specific node ID through software alone [1].

Nodes communicate with each other via two types of packets: asynchronous packets for control data and isochronous packets for real-time streaming data. Since the former adopts the client/server model, an asynchronous packet consists of a destination field (dst), a source field (src) and a payload field (data), as shown in Fig. 1. The latter relies on the publish/subscribe model where senders and receivers are unaware of each other. Thus, node addresses are not recorded in isochronous packets and an address mapping problem does not arise for this type of packets. Therefore, we will focus on only asynchronous packets in the subsequent sections.

B. Network Configuration

In order to formulate the bridging problem, we have modeled the wireless network of 1394 devices from two different viewpoints. One is the physical view, as shown in Fig. 2(a), and the other is the logical view, as shown in Fig. 2(b).

In the physical model, nodes that are connected with the same 1394 bus form a separate 1394 network segment. In each segment, there is a bridge device that connects the 1394 bus and the wireless network. As stated in the previous section, each node has a node ID which uniquely identifies the node in a 1394 network segment. Similarly, each bridge device is assigned a unique address in the wireless network. It can be a specific MAC address depending on the particular protocol used in the wireless network. We call it a bus ID since it can be used to uniquely identify a 1394 bus. Accordingly, in the physical model of the wireless 1394 network, a node is identified by a tuple (bus ID, node ID) and we refer to this as the physical address of a node. For example, the physical address of node n in Fig. 2 is (z, 1). Note that two nodes in different network segments may have the same node ID, as do nodes n and n.

In the logical model, all the nodes are considered to be connected to a single fictitious 1394 bus. The bridge devices and the wireless network are completely hidden in this model. A node in the logical bus is associated with a unique address and we call it the logical address. For example, the logical
address of $n_3$ is 2 in Fig. 2.

C. Address Mapping Problem

A bridge mechanism must allow nodes to send and receive asynchronous packets only using their logical addresses. However, in order for a packet to be correctly delivered to a destination node across the wireless network, its logical address must be translated into its corresponding physical address. Therefore, a bridge device must have a mapping table and be able to perform a packet address translation according to the table whenever a packet is forwarded. Specifically, the mapping table can be formulated as a logical-to-physical address translation function

$$f : L \to (B \times N) \cup \text{NIL}$$ (1)

where $L$, $B$ and $N$ are the set of logical addresses, the set of bus IDs and the set of node IDs, respectively. For example, $f(l) = (b, n)$ indicates that logical address $l$ maps to physical address $(b, n)$ and $f(l) = \text{NIL}$ indicates that it does not map to any physical address.

Along with the translation function, we have following two additional design requirements for practical reasons.

- C1: The logical address must be 6 bits long. Otherwise, existing legacy 1394 devices cannot be supported. Maintaining the backward compatibility is very important since a tremendous number of legacy 1394 devices are widely spread.

- C2: A bridge device must be constructed without requiring new custom 1394 hardware chipsets. The reuse of existing 1394 chipsets is preferred as they are low in price and have been extensively tested over a decade.

III. MODELING EXISTING BRIDGE MECHANISMS

The modeling framework presented in the previous section can serve as an effective tool to formulate and evaluate various bridge mechanisms. Using this framework, in this section we first model the two existing bridge mechanisms and then present our mirroring bridge mechanism in the next section.

The IEEE 1394.1 bridge uses 16 bits for a logical address where the upper 10 bits are used to identify a 1394 bus and the lower 6 bits are used to identify a node in a given 1394 network segment [1]. This implies that $L = B \times N$ and that address translation function $f$ becomes a simple identity function, such that $f((b, n)) = (b, n)$.

While the simplicity of the address translation function leads to an efficient implementation of the IEEE 1394.1 bridge mechanism, the extended logical address space requires nontrivial modifications to the PHY and LINK layer of the original 1394 standard. Therefore, existing 1394 chipsets that conform to the original 1394 standard cannot be used in either 1394 devices or bridge devices. Clearly, the IEEE 1394.1 bridge does not satisfy either requirement C1 or C2.

The transparent bridge uses 6 bits for a logical address just as in the original 1394 standard [7]. Thus, it supports interoperability with legacy 1394 devices and satisfies requirement C1 as well. On the other hand, the transparent bridge additionally mandates that a node ID in a physical address be used as a logical address in each 1394 network.
segment. This implies that \( L = N \) and that the address translation function \( f \) again becomes simple, such that \( f(n) = (b, n) \).

While the address translation function greatly simplifies address mapping, it requires that a bridge device have full control of the node ID allocation process in order that a remote node be able to have a pre-assigned node ID in a local 1394 network segment. As stated in Section II, in the original 1394 standard, node IDs are arbitrarily allocated by a 1394 hardware chipset and cannot be programmed via software. Therefore, the transparent bridge does not satisfy requirement C2.

IV. THE MIRRORING BRIDGE MECHANISM

In this paper, we formally present our mirroring bridge mechanism using the address translation function and describe how our solution strategies satisfy the two requirements of a practical 1394 bridge. In Section V, we present the detailed architecture design of a bridge device that implements our solution. Before we explain the mirroring bridge formulation, we will first introduce the notion of a proxy node.

A proxy node is a local 1394 node that emulates a remote 1394 node. It is implemented inside a bridge device. Since there is a one-to-one correspondence between a proxy node and its remote node, the node ID of a proxy node can uniquely identify the emulating remote node. Thus, we use the node ID as the logical address of the remote node. This implies that \( L = N \) and a logical address is 6 bits long. In Fig. 3, the numbers inside the gray rectangles represent the logical addresses. For example, node \( n_4 \) has logical address 3 in segment \( s_1 \).

Since the node ID of a proxy node is arbitrarily allocated in each 1394 network segment, the logical address of the same remote 1394 node may vary in different 1394 network segments. In order to resolve this logical address difference, we allow each 1394 network segment to have its own logical address space. This obviously requires a different address mapping function for each bridge device. In Fig. 3, for example, the two tables realize two address mapping functions \( f_1 \) and \( f_2 \) of the bridge devices in 1394 network segments \( s_1 \) and \( s_2 \), respectively.

For the bridge device in 1394 network segment \( s_1 \), we let \( f_1 \) and \( b_1 \) denote its address mapping function and bus ID, respectively. The bridge device constructs a mapping table for function \( f_1 \) via a three-step process. First, the bridge device waits until all local 1394 nodes, including proxy nodes, are assigned node IDs via the self-ID process of the 1394 protocol. For each node, it then allocates an entry in the mapping table with the node ID being the index of the entry. Second, for each non-proxy local node with node ID \( l \), the bridge device associates bus ID \( b_1 \) to derive its physical address \( (b_1, l) \). In Fig. 3, for example, \( f_1 \) maps logical addresses 0 and 2 into physical addresses \((x, 0)\) and \((x, 2)\), respectively. The derived physical address information is broadcast to other bridge devices. Third, for each physical address received from other bridge devices, the bridge device selects an unmapped logical address entry from its mapping table and creates a mapping entry for the physical address.

Using such a mapping table, a bridge device can perform...
packet address translation. When a packet with destination address \( d_i \) and source address \( s_i \) is sent from segment \( s_i \) to segment \( s_j \), two different types of address translations are performed.

First, destination address \( d_i \) is translated into physical address \( p_{d_i} \) by the bridge device in \( s_i \) using function \( f_i \) as below.

\[
p_{d_i} = f_i(d_i) = (b_i, d_i').
\]  

Then, the bridge device in \( s_j \) uses the inverse of function \( f_j \) to remove its bus ID \( b_j \) from \( p_{d_i} \) as below.

\[
l_j' = f_j^{-1}((b_j, d_i')).
\]  
The \( l_j' \) is the logical destination address in segment \( s_j \). The translation from \( l_i \) to \( l_j' \) can be simplified using a composition of \( f_i \) and \( f_j^{-1} \) as below.

\[
l_j' = (f_i \circ f_j^{-1})(l_i).
\]  
The source address translation is performed similarly. The bridge device in \( s_i \) translates source address \( s_i \) into physical address \( p_{s_i} \) by appending its bus ID \( b_i \) using its translation function \( f_i \) as below.

\[
p_{s_i} = f_i(s_i) = (b_i, s_i).
\]  

Then, the bridge device in \( s_j \) uses the inverse of function \( f_j \) to translate \( (b_i, s_i) \) into logical address \( s_j' \) as below.

\[
l_j' = f_j^{-1}((b_i, s_i)).
\]  

The translation from \( s_i \) to \( s_j' \) can be simplified in a similar manner using a function composition as below.

\[
l_j' = (f_i \circ f_j^{-1})(l_i).
\]  

Fig. 3 depicts an example of the packet address translation process in our mirroring bridge mechanism. In the figure, node 2 in segment \( s_1 \) sends an asynchronous packet to node 4 in segment \( s_2 \). The packet is handled in the order of actions numbered in the figure.

(1) In segment \( s_1 \), logical source and destination addresses are 2 and 3, respectively.

(2) The bridge device in \( s_1 \) translates logical source address 2 into \( f_i(2) = (x, 2) \) and logical destination address 3 into \( f_j(3) = (y, 1) \). (4) The bridge device in \( s_2 \) translates the physical source address \( (x, 2) \) into \( f_j^{-1}(x, 2) = 4 \) and the physical destination address \( (y, 1) \) into \( f_j^{-1}(y, 1) = 1 \). (5) The packet is correctly delivered to destination node \( n_4 \).

Observe that the proposed address mapping mechanism satisfies the two requirements of a practical 1394 bridge device. Our mechanism supports interoperability with legacy 1394 devices since it maintains compatibility with the original 1394 protocol by using 6 bits for a logical address. Furthermore, it does not require a custom 1394 chipset for bridge implementation since it works well with the self-ID process of the 1394 protocol.

V. THE ARCHITECTURE DESIGN OF A BRIDGE DEVICE
In this section, we provide the detailed architecture design of a bridge device that implements the proposed mirroring bridge mechanism.

As depicted in Fig. 4, our mirroring bridge hardware consists of multiple 1394 nodes and a WiMedia UWB interface card. Even though a WiMedia UWB interface card is used to exchange packets between bridge devices in this particular design, it can be replaced with any other network interface card since our bridge mechanism does not depend on a specific wireless technology.

Fig. 4 also shows the software architecture that consists of two device drivers and three modules. First, the packet forwarding module transfers packets between a 1394 network segment and the WiMedia UWB network. While transferring a packet, it also translates the destination and source addresses in the packet using the mapping table inside this module according to the process explained in Section IV.
implementing an appropriate protocol adaption module. Protocols, such as IEEE 802.11, can be easily supported by increasing the portability of our mechanism. Other wireless design and construct it as a separate module in order to extract the protocol conversion functionality from the original packet into a WiMedia UWB packet and vice versa. We table in the companion packet forwarding module. The module uses the exchanged information to update the mapping device is plugged in or is unplugged. A local bus management (3) they exchange node ID information whenever a 1394 buses in order to prevent buffer overflow and underflow; (2) they synchronize the clocks of the channel bandwidths; (1) they manage isochronous resources such as the 1394 buses in order to prevent buffer overflow and underflow; and (3) they exchange node ID information whenever a 1394 device is plugged in or is unplugged. A local bus management module uses the exchanged information to update the mapping table in the companion packet forwarding module.

Finally, the protocol adaptation module converts a 1394 packet into a WiMedia UWB packet and vice versa. We extract the protocol conversion functionality from the original design and construct it as a separate module in order to increase the portability of our mechanism. Other wireless protocols, such as IEEE 802.11, can be easily supported by implementing an appropriate protocol adaption module.

![Fig. 5. Experimental network configuration for evaluating the mirroring bridge mechanism.](image)

Second, the local bus management module basically manages communication resources and network reconfiguration by exchanging inter-bridge packets. The inter-bridge packet is a control packet exchanged between bridge devices. It does not pass through the packet forwarding module. The local bus management modules distributed over all bridge devices jointly perform three tasks using inter-bridge packets: (1) they manage isochronous resources such as channel bandwidths; (2) they synchronize the clocks of the 1394 buses in order to prevent buffer overflow and underflow; and (3) they exchange node ID information whenever a 1394 device is plugged in or is unplugged. A local bus management module uses the exchanged information to update the mapping table in the companion packet forwarding module.

VI. EXPERIMENTAL EVALUATION

We have implemented the proposed bridge mechanism in our bridge device. The bridge device is equipped with a 400-MHz PowerPC processor, 1394 interface cards and a WiMedia UWB interface card. Linux version 2.6.18 was used as the operating system and all the bridging functionalities were implemented as three kernel modules. In order to show the viability and efficiency of our mechanism, we have built an experimental network and conducted a series of experiments in the network. Specifically, we have measured its throughput and latency. Before presenting the experimental results, we will give an overview of the experimental configuration.

![Fig. 5](image)

Fig. 5 shows the configuration of the experimental network. In the network, we have three 1394 network segments, each of which consists of a bridge device and three legacy 1394 devices including HDTVs, a PC, a set-top box and a digital camcorder. The three bridge devices are connected to a WiMedia UWB network. Although the maximum data rate of the wireless network is defined as 480 Mbps in the specification [9], we set the data rate to 200 Mbps because our prototype UWB hardware chipset could not stably support the maximum data rate.

A. Measuring Throughput

For measuring the throughput, each 1394 device was configured to continuously generate traffic to arbitrary devices across the WiMedia UWB network. We then measured the maximum throughput of a bridge device and the result is shown in Table 1. The resultant throughput was 188.7 Mbps, which is 94.4% of the data rate of the UWB chipset used. The unutilized 5.6% is due to the overhead caused by inter-bridge packets and the additional packet headers for the WiMedia LINK layer [8]. Therefore, we conclude that the throughput loss is negligible when using our mirroring bridge mechanism.

We have also measured throughput in upward and downward directions. The former is the direction from the local 1394 segment to the WiMedia UWB network and the latter vice versa. As shown in the Table 1, the upward throughput was 63.0 Mbps while the downward throughput was 125.7 Mbps. The downward throughput is about twice the upward throughput. This is because the three bridge devices access the WiMedia UWB network in a TDMA manner. For each bridge, one third of the time is used sending packets and two thirds receiving packets.

![Table 1](image)

<table>
<thead>
<tr>
<th>TABLE I: Measured Maximum Throughput of Bridge Device</th>
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<tbody>
<tr>
<td>Direction</td>
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</tr>
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B. Measuring Latency

In the 1394 protocol, a packet is considered lost if a response to the packet is not received within 100 ms. Packet loss triggers the retransmission of the packet, which significantly decreases the net throughput. In order to prevent such packet retransmission due to timeout, a bridge device should not add unacceptable latency. We measured the end-to-end round-trip packet delay to show that our mechanism incurred only negligible bridging delay.

We programmed the PC to send asynchronous packets to the laptop as shown in Fig. 5. We then measured the round-trip delay of the packets. The result is shown in Fig. 6. The average, the maximum jitter and the standard deviation of the delay were 2.154 ms, 2.191 ms and 0.750 ms, respectively. The delay is only 2.2% of the 100 ms timeout value. Therefore, we can safely argue that packet losses seldom occur.

VII. CONCLUSION
In this paper, we have presented the mirroring bridge mechanism as a means of seamlessly interconnecting legacy 1394 devices over the UWB network. Unlike existing bridge mechanisms, the proposed mechanism supports interoperability with legacy 1394 devices and does not require new chipsets for the implementation of bridge devices. This is made possible through the flexible address mapping function which can be implemented entirely through software.

We have implemented the proposed bridge mechanism in our bridge devices and used them to interconnect legacy 1394 devices via a WiMedia UWB network. By conducting a series of experiments, we have shown that the overhead caused by our mechanism is negligible. Throughput was decreased by only 5.6% and latency was 2.5% of the timeout value.

REFERENCES


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