An Object-Oriented Communication Library for Hardware-Software CoDesign

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Abstract
Implementing communication between hardware and software components can be a time-consuming task. Numerous communication protocols are available, differing greatly in their implementation details. Designers must spend much time focusing on those details. Even when libraries are available to encapsulate communication into C or VHDL routines, these routines are not consistent across protocols, making it difficult to switch to other protocols. In this paper, we propose an object-oriented communication library, which provides pre-implemented channel-based send/receive communication primitives, allowing easy implementation and seamless migration across protocols and components.

1 Introduction
Systems often consist of a combination of processing components, such as microprocessors, microcontrollers, and custom ASIC/FPGA processors. Ideally, application developers would be able to develop software and hardware code using abstract send/receive primitives for communication, based on a communicating sequential processes (CSP [1]) paradigm as proposed in [2], for example. A primitive’s underlying implementations, such as the choice of a particular bus type and protocols, the assignment of communications to ports, and the setting and reading of interface registers and port signals, would be hidden or created later.

However, there is presently a gap between message passing primitives and their implementations, as illustrated in Figure 1. For some architecture and protocols, some abstract communication primitives do exist, though most fall far short of send/receive primitives; for example, ISA bus transfers of a PC [3] are achieved using in and out assembly instructions, and serial transfers of an Intel 8051 are achieved by configuring several registers [4]. For other architectures and protocols, direct port manipulation is necessary, such as for most transfers for an FPGA or microcontroller. This gap means that developers must spend much effort learning numerous varied communication details and testing those communications. While developers have certainly built subroutines to hide those details, to our knowledge there is no published library of routines that supports a message passing paradigm while being consistent across architectures and platforms.

We are therefore developing an object-oriented communication library (OOCL). OOCL provides C (or C++) and VHDL send/receive communication primitives for numerous common protocols and components, with pre-tested underlying implementations. A designer chooses an OOCL channel supporting the desired protocol, without needing to focus on underlying implementation details. A user instantiates a communication channel object, initializes it, and then sends or receives messages over it; all access to low-level ports, registers, and communication behavior is hidden in the object’s implementation. Because OOCL is a library, existing languages like C and VHDL need not be modified, and no synthesis tools are required to generate the communication behaviors (though synthesis and compilation are obviously necessary to implement those behaviors). Instead,
OOCL needs to be ported to new architectures, just as any other library (such as a math library) must be ported.

The OOCL approach complements related codesign interface research. In [5], a solution is proposed that automates the hardware-software interface using minimum glue logic, while satisfying timing constraints. To communicate with a peripheral device, the processor generates a sequence of signals (SEQs) that read and write the device's ports. Symphony [6] defines a standard communication protocol for all processor components, using send and receive operations with a synchronous wait protocol, where the sender asserts a ready signal and then waits for the receiver to assert its own ready signal. In [2], a codesign methodology is discussed using process communication primitives that allow three types of process interaction: synchronized data transfer, unsynchronized data transfer and synchronization without data transfer. In [7], a system design methodology is discussed using abstract send/receive channels for communication. In all of these approaches, OOCL can be used to encapsulate the communication using send/receive primitives, while implementing the protocol, without any modification to the C or VHDL languages.

Operating systems often include abstractions for communication, such as remote procedure calls (RPCs), mailboxes, and inter-process communications (IPCs). However, most of these are not supported by custom processor components and microcontrollers, since such devices do not usually have an operating system.

OOCL is intended for use when at least one of the communicating components has flexible ports usage, such as a microcontroller or an FPGA, or when two fixed components use the same protocol, such as the PC RS232 serial protocol, to interface two components having fixed incompatible protocols, either an interface process [8] or interface transducer [9] must be generated.

2 Using the library

We introduce use of OOCL with the simple public-key encryption example of Figure 2; the details of the encryption algorithm are not shown. A portable data-entry device (using an 8051 microcontroller) downloads its data in encrypted form to a PC, which requires that it first receives two public encryption keys from the PC. The communication occurs between one of the PC's serial ports, which uses the RS232 protocol, and the 8051's built-in UART and its associated ports, along with additional general ports for control, as shown in Figure 2(a). Figure 2(b) shows the C code required by the 8051 to achieve its part of the communication, without the use of OOCL; complementary code would exist on the PC. Note that this communication code is non-trivial, requiring knowledge of many low-level details. The programmer must study the details of the serial protocol, referring to pin configurations, architectural details and timing diagrams. This inevitably results in the user having to iterate a few times to make the communication code error free.

Figure 2(c) shows the same code re-written using the OOCL routines. Having decided to use a PC and 8051 communicating over the PC's serial port, the user first selects the appropriate PC serial channel objects from OOCL in Figure 2(d). The user then declares a channel key_chan for receiving the keys, and another channel msg_chan for sending encoded data. The user then initializes these channels, in this case choosing the default initialization ports and speed, and then performs sends and receives over those channels. Note that the user is presented with abstract message passing, as desired,

Figure 2: (a) Block diagram for the RSA system, (b) user code without and (c) with the OOCL routines using the RS-232C serial protocol, (d) library routines.
even though underlying implementations do exist.

The reduction in code size and development time is significant, but even more significant advantages are seen when we change the communication. Suppose we choose to use the PC's parallel port instead of the serial port to speed up the data transfer. Such a change would require a complete rewrite of the code in Figure 2(b), in addition to the study of the new protocol and the testing of the implementation. However, when using OOCL, such a change merely involves selecting a new channel object from the library, i.e., replacing PCS in Figure 2(c) by PCP. Alternatively, suppose we decide to use the PC's ISA bus for the transfer for even more speed. This change requires a device faster than an 8051, so we might choose an FPGA. Once again, the communication code would only change slightly when OOCL is used, i.e., just declare a different channel type, but would require a complete rewrite without OOCL.

3 Library implementations

We now discuss the underlying implementations for two example protocols.

3.1 PC serial protocol

Information is frequently transferred to a PC, either as integral part of the design itself or as down-load information from an application. The RS-232C standard for serial interfaces is suitable for applications where lower data-transmission rates are acceptable, and the transmission is over short distances or when a limited number of I/O pins are available for communication. This protocol is especially suitable for slower devices like the 8051 which cannot keep up with the faster transfer rates of the ISA or PCI bus. The TTL logic level signals need to be converted to the non-TTL interface needed by the RS-232C standard.

The receiving device controls the flow of data from a transmitting device. Hardware handshaking is used for developing the PCSerial communication library routines. This type of handshaking uses dedicated circuits to control the transmission of data. Figure 2(a) showed the block diagram of a PC and an 8051 microcontroller connected via a serial interface. On the PC side, the user can use any one of the available RS-232C serial ports. The RS-232C/TTL drivers/receivers interface the RS-232C and TTL voltage levels.

The transmit data (txd.p) and receive data (rxd.p) lines run from the PC to the UART data ports, which are P3.1 and P3.0 respectively, on the 8xc51. sgg is the RS-232C signal ground. The control handshake signals, data terminal ready (dtr.p') and request to send (rts.p') run from the PC to the 8xc51, while the data set ready (dsr.p') and the clear to send (cts.p') are the control signals from the 8xc51 to the PC. General purpose 8xc51 I/O ports can be used for the control lines.

We now describe the naming conventions used by OOCL. Active low logic is indicated by appending a ’. The communication ports are indicated by appending “.p”. For example, ack.p indicates a port that is active low. Declarations that are part of the library are indicated in upper-case and are prefixed with “CL” e.g., CL_PARITY_NONE. Other declarations are indicated in upper-case and are not prefixed with “CL”. Variables are indicated in lower case, with an underscore if needed. The following fields are used in a channel name and are separated by an underscore:

- A channel name is prefixed with “CL” to indicate that is a communication library channel.
- The next field is “SEND” or “REC” to indicate whether the channel will be used to send or receive messages.
- This is followed by “M” or “S” to describe whether it is associated with a master or servant process. The master process initiates the transfer.
- An abbreviation for the protocol used is next, which may include additional information if needed.
- Finally “A” can be appended to distinguish the addressed mode of communication from the point-to-point mode.

Figures 3 and 4 show the OOCL routines, which use the PCSerial protocol for the PC and 8xc51 respectively. The figures show the PC send and the 8xc51 receive channels. The complementary channels are similar. Each channel type’s library entry consists of declarations, initializations, and send/receive transfers.

**Declarations**: The PC send channel is declared as CL_SEND_M_PCS while the 8xc51 receive channel is called CL_RECV_S_PCS, conforming to the CL naming convention. The data members for the PC send channel are rxd.p for the data, dtr.p and cts.p for the control, and port_ads to store the serial port address.

The 8xc51 receive channel includes rxd.p for the data, and dtr.p and cts.p for the control lines. The channel member functions for accessing the ports (inp()) and outp() for the PC, and SetPortBit() and GetPortBit() for the 8xc51) are accessible only to the OOCL routines.

**Initializations**: While using the OOCL routines for the PC, the user can call the default initialization. In this case, the communication parameters are set to COM1, which is usually the 9-pin serial port, 2400 baud, no parity, 8 data-bits, and 1 stop-bit. Otherwise the user could call the non-default initialization by specifying the communication parameters. In both these cases, the port addresses are fixed registers. Similarly, when
Declare Channel

class CL_SEND_M_PCS
{
  uin uin_p, p; // transmit data line
  uchar ddr_p, ccs_p; // handshake signals
  port p; // serial port address
  Set the baudrate
  void baudSetRate(port, long baud_rate);
  Set the parity, data bits, stop bits
  void compadpmtDataBits(data_bits, stop_bits);
  // Read, write to an I/O port
  port port_add;
  void comtart_add(char add, uchar value);
  public:
    // Initialize ports to default values
    void InitDefault();
    // Initialize ports to user specified values
    void InitPort(char add, uchar value);
    // Send the message (character)
    void SendCharMessage();
};

Initialize channel (default)

class CL_SEND_M_PCS::InitDefault()
{
  port_add = CL_MSTAT_DSR;
  ccs_p = CL_MSTAT_CTS;
  // Default initialization is port.COMM, 9600
  // no parity, 8 data bits and 1 stop bit
  port_add = CL_PCS_PORT.COMM;
  tdr.p = CL_REG.TX;
  baudSetRate(port_add, 9600);
  // Compare CL_PCS_PARITY, 0; 0; CL_PCS, 0; STOPBITS, 1; CL_PCS, 0; DATABITS, 0; 8;
  // Turn off handshaking
  // KeepCL_REG.MOINT, 0; 0;
}

Send message (character)

class CL_SEND_M_PCS::SendCharMessage()
{
  // Lowest four bits
  int uata = 0;
  // Lowest four bits
  int uata = 0;
  // Device asserts DSR when it is ready to receive
  do { uata = inport(CL_REG.MSTAT); } while (uata & ddr_p);
  // Device asserts CTS after receiving
  do { uata = inport(CL_REG.MSTAT); } while (uata & ccs_p);
  // Read the character once received. from the UART register
  // Wait for both DSR and CTS to go low
  do { uata = inport(CL_REG.MSTAT); } while (uata & ddr_p);
  do { uata = inport(CL_REG.MSTAT); } while (uata & ccs_p);
  // Receive the message (character)
  // KeepCL_REG.MOINT, 0; 0;
}

3.2 Custom protocols

Many components, such as microcontrollers and FPGA's, have ports which are flexible, not having a pre-defined use. In other words, the component's program or circuit can set and read these ports in any manner desired. Flexible ports are in contrast to fixed ports, like those associated with the ISA bus, which have a specific purpose (e.g., request, acknowledge, interrupt, data, or address). When two components can communicate using flexible ports, custom protocols are required.

There are several characteristics that a custom protocol behavior may possess. We can taxonomize these characteristics as follows:

- Master versus Servant: A master behavior initiates a send or a receive data transfers, using a request port. The servant must respond to such
requests by either receiving or sending the data.

- Sender versus Receiver: Each channel may be either for sending or receiving.
- Data size: Data must be encoded into some number of bits in order to be transferred.
- Data bus size: The data bus uses some number of ports, which may be less than the data size, in which case a number of "chunks" are sequentially transferred.
- Four-phase versus two-phase handshaking: In two-phase handshaking, the master asserts the request signal, waits for a specified time, and then de-asserts the signal and proceeds. In four-phase handshaking, the master asserts the request signal, but then waits for the servant to assert and acknowledge signal, only then proceeding. Four-phase communication achieves synchronized data transfers, while two-phase is faster when synchronization can be ensured by other means.
- Point-to-point versus Addressed mode: A master may have many servants, in which case the master must provide an address along with a request. If there's only one servant (point-to-point), then no address is required.
- Address bus size: If an address is used, its size must be known.

We point out that multiple channels may share the same ports. The actual binding of abstract channels to ports is done during the initialization of the channel; in the same manner, address and data may also share ports.

Figure 5 shows the block diagram for a two-phase addressed data transfer between two 8xc51s, a liquid crystal display (LCD) and an FPGA. At a given time, only one of these devices can act as the master on the bus, the figure shows this to be an 8xc51. All the devices on the bus share a 8-bit bidirectional data port. An 8-bit address port runs from the master to each servant on the bus. In addition, an address request line (addr Req. p) and a data request line (req. p) also goes from the master to each servant. General purpose 8xc51 I/O ports are used for the address, data and control lines.

Figures 6 and 7 show the OOCL routines for the master and servant 8xc51s respectively, which use the two-phase addressed protocol. The figures show the master send channel and the servant receive channel. The complementary channels are similar. Each channel type's library entry consists of declarations, initializations, and send/receive transfers, consistent with the OOCL methodology. Only one servant device is addressed at a time and that device responds within the two-phase delay.

Figure 5: Bus connections for the two-phase addressed protocol using an eight-bit data port.

A number of OOCL routines have been developed to support custom protocols; we omit details here. Because of the large number of combinations of protocol characteristics, there are a large number of custom routines. For this reason, OOCL currently supports a subset of possible characteristic values: data size is 8, data bus size may be 8, 4, or 1, and address size is equal to the data bus size.

3.3 Other protocols

We have developed an initial library for a number of protocols. For PC's, we have C routines for the serial port and for the ISA bus, and preliminary routines for the PCI bus. For 8051 microcontrollers, we have C routines for custom protocols, the PC serial protocol, and the Inter-Integrated Circuit (I2C) serial bus. For custom hardware (FPGAs and ASICs), we have VHDL routines for custom protocols, ISA and PCI.

4 Conclusions

OOCL bridges the gap between the abstract message passing primitives desired by the user, and the underlying communication implementation. It provides a consistency across diverse protocols and hardware-software components. Because OOCL is based on libraries, no additional tools are needed to generate the interface, and no language extensions are necessary. In addition to supporting the initialization, send and receive methods, the OOCL servant channels have been enhanced with methods that determine if the channel is ready to send or receive data, and with other routines that then proceed to complete the transfer. This enables the OOCL methodology to be applied to multiple processing in software using interrupts or a RTOS, or in hardware using a bus controller.

Future directions include expanding the library to include other common protocols, and investigating automated generation of the library routine implementa-
Figure 6: OOC1 code extract for the two-phase addressed protocol using an eight-bit data port: master send

Figure 7: OOC1 code extract for the two-phase addressed protocol using an eight-bit data port: servant receive.

References


