TinyLink: A Holistic System for Rapid Development of IoT Applications

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Rapid development is essential for IoT (Internet of Things) application developers to obtain first-mover advantages and reduce the development cost. In this article, we present TinyLink, a holistic system for rapid development of IoT applications. The key idea of TinyLink is to use a *top-down* approach for designing both the hardware and the software of IoT applications. Developers write the application code in a C-like language to specify the key logic of their applications, without dealing with the details of the specific hardware components. Taking the application code as input, TinyLink automatically generates the hardware configuration as well as the binary program executable on the target hardware platform. TinyLink provides unified APIs for applications to interact with the underlying hardware components. We implement TinyLink and evaluate its performance using real-world IoT applications. Results show that (1) TinyLink achieves rapid development of IoT applications, reducing 52.58% of lines of code on average compared with traditional approaches; (2) TinyLink searches a much larger design space and thus can generate a superior solution for the hardware configuration, compared with the state-of-the-art approach; (3) TinyLink incurs acceptable overhead in terms of execution time and program memory.

CCS Concepts: • **Computer systems organization** → *Embedded software*; System on a chip; • **Hardware** → Sensor devices and platforms;

Additional Key Words and Phrases: Internet of Things, rapid development

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1 INTRODUCTION

Over the past years, the Internet of Things (IoT) [19] has evolved from a vague concept to practical systems connecting lots of network devices, and it is considered as a promising future computing

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technology [12]. IoT platforms are tightly coupled to their applications [22, 27, 40]. This coupling makes it difficult for general-purpose platforms to address application-specific needs [21].

The lack of general-purpose IoT platforms causes difficulties in developing IoT applications. Developers have to know all aspects of an IoT system, including the requirements of target application as well as the hardware components and the software components. They typically follow a *bottom-up* approach from building an appropriate hardware platform (consisting of appropriate microcontrollers and different sensors) to writing application software that can run on the platform [23, 42, 44]. This bottom-up approach is time-consuming [30]: an individual application developer has to learn and build a hardware platform first, then construct the software libraries, and finally write the application code; an application developer in a team has to wait for others to complete the hardware platform and the software system before he/she can write application code.

In this article, we advocate a *top-down* approach: an application developer can first write the application code as if there exists a virtual platform which *possesses* all hardware components in the market. An intelligent system takes the application code as input and will (1) automatically generate concrete configurations for hardware platforms (e.g., which components to select and how they connect); and (2) translate the hardware-independent application code into hardware-dependent code which can directly execute on the generated hardware platform. This top-down approach greatly *accelerates* the developing process. While our previous position paper suggested the promise of this top-down approach [25], it fell short of answering several practical challenges, which we address in this article.

First, how to select the most appropriate hardware components in order to satisfy application requirements? User-desired functionalities can be inferred from the application code. How to select the hardware components accomplishing all the desired functionalities? Considering different costs and different characteristics of these hardware components, how to formulate this hardware selection problem and which optimization criterion should be chosen?

Second, how to embrace a diverse set of commercially available hardware components in a compatible manner? Significant hardware innovation has occurred recently, particularly in the Maker domain around Arduino and Raspberry Pi platforms. There has been a move from fixed platforms toward platforms with high extensibility. For example, mainboards already offer many interfaces, *e.g.*, port and physical pin. Shield (a.k.a. expansion board) offers more flexibility for peripherals to interface with the mainboard. How to consider complex connections between peripherals and the mainboard?

Finally, how to express application logic in a hardware-independent manner and translate it into the executable code for the corresponding hardware configuration? Abstracting a unified programming environment is difficult as different platforms support different environments, e.g., Arduino supports the AVR programming environment, and Raspberry Pi supports the ARM-based Linux programming environment. How to implement a holistic system so that application developers need not care about low-level details such as device drivers, cross-compilers, and so on?

In order to address the above challenges, we present TinyLink, a holistic system for rapid development of IoT applications. With TinyLink, developers can specify application logic in a C-like language, without dealing with the details of the underlying hardware, drivers, compilers, and so forth. Taking the application code as input, TinyLink automatically generates hardware configurations as well as the hardware-dependent code executable on the target hardware platform.

TinyLink includes a hardware database containing commercial-off-the-shelf (COTS) hardware components as well as their characteristics (e.g., costs, interfaces, required voltage). Based on the hardware database, TinyLink explicitly formulates possible compositions as hardware constraints. TinyLink carefully considers possible connections between ports and physical pins provided by mainboards and shields and thus can embrace a diverse set of COTS hardware components.

TinyLink also extracts the user constraints from the code, e.g., the invocation of a TinyLink API `TL_GPS.read()` means that one GPS sensor is required. TinyLink explores the design space by considering both hardware constraints and user constraints. Currently, TinyLink adopts an optimization criterion to minimize the cost. Other criteria (e.g., extensibility, energy, and performance) can also be adopted. TinyLink seeks the best solution by solving the optimization problem and outputs the hardware configuration (consisting of the set of hardware components and their connections).

TinyLink reuses easy-to-use Arduino-like environment for application programming. TinyLink provides unified APIs for the application to interface with the underlying hardware components. The APIs are fully implemented on four mainboards, including Arduino UNO, Raspberry Pi 2, BeagleBone Black, and LinkIt ONE. To minimize the implementation overhead, TinyLink heavily reuses existing libraries. Glue code is implemented in TinyLink, serving a binding from the APIs to existing libraries TinyLink builds upon.

TinyLink is a holistic system: besides generating hardware configurations and providing easy-to-use APIs, TinyLink also includes (1) Cloud-based compiling architecture; (2) Web-based application programming interface; and (3) commonly used benchmarks for system validation.

We evaluate TinyLink using real-world IoT applications. Results show that (1) TinyLink achieves rapid development of IoT applications, reducing 52.58% of lines of code on average compared with existing programming approaches for Arduino UNO, Raspberry Pi 2, BeagleBone Black, and LinkIt ONE; (2) TinyLink searches a much larger design space and thus can generate a superior solution for the hardware configuration, compared with CodeFirst [24]; and (3) TinyLink incurs acceptable overhead in terms of execution time and program memory. Moreover, we present four concrete case studies and one user study that illustrate how TinyLink can help us quickly develop real-world IoT applications.

The contributions of this work are summarized as below:

- We present TinyLink, a *holistic* system for developing IoT applications. TinyLink transforms the IoT development process from *bottom-up* to *top-down*, enabling *rapid* development of IoT applications. TinyLink abstracts away the IoT hardware so that developers can focus on the application logic without experience in embedded systems.
- We formulate the hardware selection problem as an optimization problem. We carefully consider *hardware constraints* and *user constraints* so that a wide range of COTS hardware components can be used in a compatible manner and application requirements can be satisfied.
- We design unified APIs for applications to interface with COTS hardware components. We implement the APIs on four mainstream platforms so that application developers need not deal with low-level hardware details.
- We carefully evaluate TinyLink using benchmarks, four concrete case studies, and one user study. Results show that TinyLink achieves rapid development of IoT applications and generates optimal solutions for hardware configuration while incurring acceptable overhead.

The rest of this article is structured as follows. Section 2 introduces how to use TinyLink. Section 3 shows TinyLink's design overview. Section 4 and Section 5 describe the hardware generation system and the software generation system, respectively. Section 6 shows the evaluation results. Section 7 discusses some important open issues. Section 8 describes the related work, and finally, Section 9 concludes this article and gives future directions of work.

2 TINYLINK USAGE

In this section, we describe how to use TinyLink for IoT application development. We first present an application example using TinyLink, followed by describing its details.

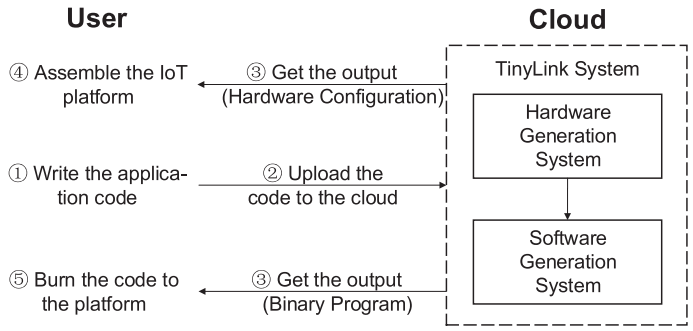


Fig. 1. Workflow overview of TinyLink.

```
1  void upload();
2  void setup() {
3      TL_WiFi.init();
4      TL_WiFi.join("SSID","PASSWORD");
5      TL_Light.setMeasuringRange(1,30000,"LUX");
6      TL_Light.setADCResolution(10);
7  }
8
9  void loop() {
10     TL_Light.read();
11     TL_Soil_Moisture.read();
12     upload();
13     TL_Time.delayMillis(60000);
14 }
15
16 void upload() {
17     double light = TL_Light.data();
18     double sm = TL_Soil_Moisture.data();
19     String url = "http://hostname/ul.php?";
20     url += String("light=") + String(light);
21     url += String("&sm=") + String(sm);
22     TL_WiFi.get(url);
23 }
```

Fig. 2. Application code example.

2.1 Example

In this example, we present the development of an IoT application using TinyLink for monitoring the moisture and ambient light of a houseplant. As shown in Figure 1, a developer needs to perform the following five steps:

① **Write the application code.** Developers can directly write the application code in a *hardware-independent* way. For example, Figure 2 shows our implementation. First, the `setup()` function is executed for the initialization of the required modules (i.e., the WiFi module). Second, the `loop()` function is continuously executed to read the sensor data and upload the data via the WiFi module. Applications can directly invoke functions of the modules via TinyLink built-in APIs which are prefixed with "`TL_`."

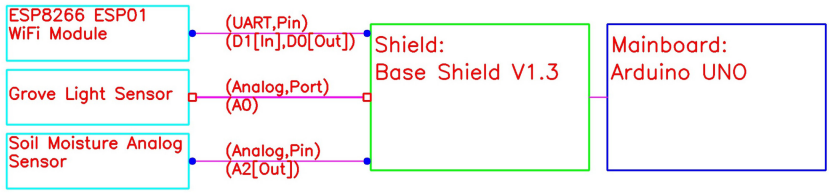


Fig. 3. Hardware connection for the example.

② **Upload the code to the cloud.** The TinyLink system runs at the cloud. Taking the application code as input, TinyLink executes multiple tasks, and the results will be returned to the developer.

③ **Get the outputs.** The developer gets the following two outputs: (1) the hardware configuration which includes the selected hardware components as well as their connections. TinyLink visualizes the result so that developers can easily follow the configuration to assemble the hardware platform. For example, Figure 3 shows the visualization of the hardware configuration which includes an Arduino UNO, a Base Shield V1.3, a Grove Light Sensor, a Soil Moisture Analog Sensor, and an ESP8266 ESP01 WiFi module; (2) the hardware-dependent code. TinyLink transforms the hardware-independent application code into hardware-dependent binary code which can directly run on the target hardware platform.

④ **Assemble the IoT platform.** Given the visualization of the hardware configuration (e.g., Figure 3), developers can easily assemble the selected components into an IoT platform.

⑤ **Burn the code to the platform.** The developer can then burn the hardware-dependent code onto the hardware platform to execute the desired functionalities.

It is worth noting that this top-down development approach differs drastically from the traditional bottom-up approaches and can greatly accelerate the entire IoT developing process. With TinyLink, developers can easily express the application logic without dealing with hardware details. Also, the hardware engineering efforts can greatly be reduced since TinyLink automatically handles complex hardware compatibility issues.

2.2 TinyLink Programming

We consider ease of programming as a primary design goal of TinyLink. TinyLink borrows the program structure from Arduino programming. This is because (1) it is fairly simple and (2) it is already very familiar to a large community. As shown in Figure 2, the application code built on top of TinyLink includes two primary functions.

`setup()`. The `setup()` function runs only once when the program starts. Developers can put the initialization of the required components or other one-shot tasks in this function. As shown in Figure 2, the program first initiates the WiFi module (line 3), and configures it by setting the SSID and the password of the AP (line 4). Developers can also specify additional features of hardware components, e.g., the measurement range (line 5) and the ADC resolution (line 6) of a light sensor.

`loop()`. The `loop()` function will be continuously executed after the `setup()` function. The `loop()` function usually includes some periodical tasks. As shown in Figure 2, the program reads data from the light sensor and the soil moisture sensor. Then the program invokes the function `upload()` to upload the data to the cloud server. Finally, the program invokes a built-in API to sleep for 1 minute (line 13) and then the loop restarts again.

It is worth noting that TinyLink also supports other programming styles, such as the event-driven model of TinyOS, and the protothread programming style of Contiki OS. TinyLink can support different programming styles by further encapsulating TinyLink APIs which are

implemented in various TinyLink libraries. The current implementation already supports event-driven programming through asynchronous calls and callback functions.

TinyLink provides a keyword, `REQUIRE`, for explicitly specifying a required module. In the following, we give two examples.

(1) `REQUIRE Light;`—This statement specifies that the IoT platform must include the light sensor even if the light sensor is not used in the application code; and
(2) `REQUIRE DBGPrint;`—This statement specifies that the IoT platform must include an additional UART interface for printing out debugging information.

TinyLink provides many hardware-independent APIs for developers. The details will be described in Section 5.2.

3 TINYLINK DESIGN OVERVIEW

We describe TinyLink's design goals and the corresponding approaches we have adopted.

—**Rapid IoT application development.** To achieve this goal, TinyLink (1) adopts the *top-down* development model for IoT applications; and (2) generates the hardware configuration and the binary program *at the cloud* so that there is no installation of local developing environments.
—**Ease of programming**. To achieve this goal, TinyLink borrows the simple program structure of Arduino programming. In addition, TinyLink provides *hardware-independent* APIs to facilitate application programming.
—**Little hardware engineering efforts.** TinyLink incorporates a hardware database with clear specifications of hardware components and their characteristics. The generation of the hardware configuration is formulated as an optimization problem with constraints inferred from the application code. By solving the optimization problem, TinyLink *automatically* generates the best hardware configuration.
—**High extensibility to accommodate many hardware components.** TinyLink is designed to embrace a set of COTS hardware components. Unlike CodeFirst [24], we do not assume a fixed mainboard. In addition, we need to consider complex connections between interfaces on hardware components. Finally, we need to carefully consider the implementations of libraries so that developers can easily interface with the underlying hardware components.

Figure 4 depicts the TinyLink system architecture, including the hardware generation system (Section 4) and the software generation system (Section 5). The application code serves as the input of TinyLink and is passed to both generation systems:

—Inside the hardware generation system, the hardware configuration generator automatically generates the hardware configuration by analyzing the application code and considering the information from the hardware database. The hardware generation system also generates the hardware configuration header file.
—Inside the software generation system, the cross compiler takes three sources as inputs, namely, the application code, the generated hardware configuration header file, and libraries. Finally, the binary program for the target platform is generated.

4 HARDWARE GENERATION SYSTEM

In this section, we describe the TinyLink hardware generation system from two aspects: the hardware database (Section 4.1) and the hardware configuration generator (Section 4.2).

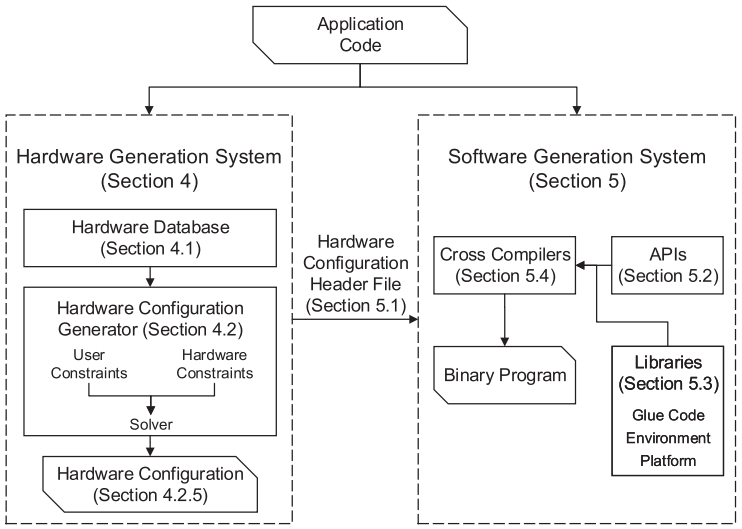


Fig. 4. TinyLink system architecture.

4.1 Hardware Database

TinyLink includes a hardware database containing COTS hardware components and their characteristics. This hardware database serves as the key information source to automatically generate hardware configurations. We look for popular and widely used COTS hardware components for embedded and IoT development and find that many platforms consist of three kinds of components:

- —Mainboard. A mainboard contains key electronic components of a system, e.g., MCU and memory. It also provides interfaces (in the forms of physical pin or port) for other peripherals.
- —Shield. A shield can be plugged onto the mainboard to transform or extend the types or number of interfaces. Also, shields with built-in modules will consume interfaces and provide functionalities, e.g., WiFi Shield V2.0 consumes UART pins and provides WiFi functionality. Moreover, some shields containing MCUs can provide extra interfaces, e.g., GrovePi+ [7] has an ATmega328 MCU and provides three extra Analog pins for Raspberry Pi.
- —Peripherals. A peripheral can connect to a mainboard or a shield via interfaces. Peripherals include input devices (e.g., sensors), output devices (e.g., display modules), and input/output devices (e.g., communication modules).

Correspondingly, our database includes three tables. Table 1 shows a simplified table which contains the following key fields: ID, cost, provided interface, consumed interface, provided MCU pin, consumed MCU pin, and functionality. For LinkIt One, it (1) costs 59 dollars; (2) has three Analog pins and two UART pins (the example only shows two types); (4) has one UART port; (5) has exposed three Analog MCU pins and two UART MCU pins; (6) occupies none of the interfaces and MCU pins; and (7) has functionalities of GPRS, GPS, SD, WiFi, and BLE integrated into the mainboard.

As shown in Figure 5, physical pins and ports are two major kinds of interfaces on IoT components. In addition, MCU or System on Chip (SoC) usually contains several to dozens of general-purpose input/output pins (GPIO), which we call MCU pins. The physical pins and ports

Table 1. Database Example

Component	ID	Cost	Provided Interface				Consumed Interface				Provided MCU Pin		Consumed MCU Pin		Functionality
			Analog Pin	UART Pin	Analog Port	UART Port	Analog Pin	UART Pin	Analog Port	UART Port	Analog	UART	Analog	UART	
Arduino UNO	1	$21.99	6	2	0	0	0	0	0	0	6	2	0	0	LED
LinkIt One	2	$59.00	3	2	0	1	0	0	0	0	3	2	0	0	LED, GPRS, GPS, Storage, WiFi, BLE
BetaBlocks	3	$75.00	0	0	2	1	0	0	0	0	4	2	0	0	LED
Raspberry Pi 2	4	$39.50	0	2	0	0	0	0	0	0	0	2	0	0	Serial
WiFi Shield V2.0	5	$39.95	6	2	1	0	6	2	0	0	0	0	0	2	WiFi
Base Shield V1.3	6	$8.90	6	2	2	1	6	2	0	0	0	0	0	0	-
Grove Light Sensor	7	$2.90	0	0	0	0	0	0	1	0	0	0	2	0	Light
Soil Moisture Analog Sensor	8	$3.98	0	0	0	0	1	0	0	0	0	0	1	0	Soil_Moisture
Grove Moisture Sensor	9	$4.90	0	0	0	0	0	0	1	0	0	0	2	0	Soil_Moisture
Grove Temp.&Humid. Sensor Pro	10	$14.90	0	0	0	0	0	0	0	0	0	0	0	0	Temp., Humidity
ESP8266 ESP01 WiFi Module	11	$6.95	0	0	0	0	0	2	0	0	0	0	0	2	WiFi
Grove UART WiFi Module	12	$13.90	0	0	0	0	0	0	0	1	0	0	0	2	WiFi

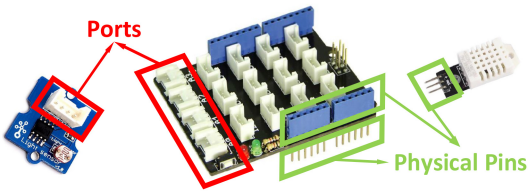


Fig. 5. Physical pins and ports.

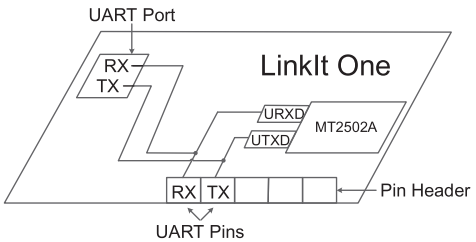


Fig. 6. Internal connections of UART pins, UART ports, and UART MCU pins on LinkIt One.

are wirings to MCU pins. For example, in Figure 6, the UART pins (i.e., RX and TX) and the UART port are wirings to the UART MCU pins (i.e., URXD and UTXD).

4.2 Hardware Configuration Generator

IoT has a diverse set of applications for different scenarios. Although some applications can use a powerful mainboard with abundant inferences, others cannot. Due to form factors, cost, and other factors, the most appropriate hardware component may be resource-constrained. The generation process intends to address the problem of how to assemble COTS hardware components in an effective and compatible way.

We first describe the conditions for a valid/compatible hardware configuration. We then formulate the hardware selection problem, i.e., which hardware components should be selected to form the IoT platform. Finally, we generate the hardware connections and visualize the final results for the developers.

4.2.1 Valid Hardware Configuration. In TinyLink, it is important to clearly define a valid hardware configuration before we can search for a valid hardware configuration. We first define a valid connection between two hardware components via interfaces. A valid connection should satisfy the following conditions: (1) the two interfaces must be in the same form (i.e., physical pin or port); (2) the two interfaces must be type compatible. Usually, it means that the two interfaces have the

Table 2. Implemented Constraints in TinyLink

Constraint	Description
Mainboard	Only one mainboard exists in a hardware configuration.
Interface	For each type of the interface, the number of consumed ones should be smaller than the number of the provided.
Power Supply	The supplied voltage level should be compatible with the working voltage level.
Drawn Current	The total drawn current of all components should be smaller than the input current; the drawn current of an interface should be smaller than the maximal allowable current.
MCU Pin	The number of consumed MCU pins should be smaller than the number of the provided.
Compatibility	All components should be compatible with each other in terms of form factor, communication, etc.
Alternative Type	All the interfaces which have alternative types can use at most one type at a time.

same type, e.g., UART. In practice, we also consider the special case in which an interface can have two or more alternative types; (3) the interfaces must be power compatible, i.e., the supplied voltage level of an interface is compatible with the working voltage level of the other interface, and the drawn current should be smaller than the maximal allowable current of both interfaces.

In a valid hardware configuration, all connections must be valid. To simplify the configuration, we first assume that there is only one mainboard. In addition, it should satisfy the following conditions: (1) the configuration must satisfy all the application requirements; (2) a connection is a one-to-one mapping. In other words, an interface cannot connect to multiple interfaces of another component since it will cause signal interference. It also means that the provided number of interfaces must be no smaller than the consumed number of interfaces with respect to a particular interface type (e.g., UART); (3) only one connection can be established on interfaces which are wiring to the same MCU pin. As shown in Figure 6, either the UART port or the UART pins can be connected at a time. A detailed example will be described in Section 4.2.4.

Table 2 summarizes the conditions we have considered in the current implementation of TinyLink.

There are several important points worth emphasizing. First, TinyLink has a much larger design space than previous approaches like CodeFirst [24]. For example, CodeFirst only allows connections between ports while TinyLink allows connections between pins which are common cases for many peripherals such as Soil Moisture Analog Sensor and ESP8266 WiFi module. Second, the conditions we have considered for a valid configuration are never exhaustive [37]. It is possible that a valid hardware configuration generated by TinyLink could not work due to conditions we have not considered, e.g., an incompatible baud rate of UART. Nevertheless, TinyLink is valuable since it helps developers avoid numerous invalid hardware configurations. In addition, TinyLink can be easily extended to accommodate additional conditions in the future.

4.2.2 Problem Formulation. We first introduce the following notations.

- M, S, P. We use them to denote the sets of mainboard, shield, and peripheral, respectively. In the database example in Table 1, $M = \{1, 2, 3, 4\}, S = \{5, 6\}, P = \{7, 8, 9, 10, 11, 12\}$.
- U, F. We use F to denote the set of all functionalities. We use U to denote the set of user-required functionalities. U can be inferred from the application code. U is included in F.
- i, d_i, c_i, f_i^u. We use d_i to denote the indicator variable. $d_i = 1$ indicates that hardware component i is present in the final IoT platform, where $i \in \{M \cup S \cup P\}$, while $d_i = 0$ indicates

that it is not. c_i is the cost of the component i. f_i^u is the Boolean value (i.e., 1 and 0) indicating whether the component i has the required functionality of $u \in U$ or not.
— t, T. We use t to denote the type of an interface, where t is in the interface type set T = {UART, Analog, SPI, I^2C, PWM, USB, Digital}.
— $NO_i^+(t), NO_i^-(t)$. $NO_i^+(t)$ represents the number of interfaces with the type t in the form of port provided by the component i, while $NO_i^-(t)$ represents the number of interfaces with the type t in the form of port consumed by the component i.
— $NI_i^+(t), NI_i^-(t)$. Similar to the notations for ports, where NI represents the number of physical pins.
— $NM_i^+(t), NM_i^-(t)$. Similar to the notations for ports and physical pins, where NM represents the number of MCU pins.

With the above definitions, the hardware selection problem can be formulated as follows with the optimization criterion being the total cost.

$$\begin{aligned} &\text{Find the values of } d_i \ (\forall i \in \{M \cup S \cup P\}) \\ &\min \sum_{i \in \{M \cup S \cup P\}} d_i c_i \\ &\text{s.t.} \begin{cases} \text{User Constraints} \\ \text{Hardware Constraints} \end{cases}. \end{aligned} \tag{1}$$

Component i is selected iff $d_i = 1$. We call a set of i's as a feasible set if they satisfy all the constraints. In the following, we describe how we carefully set up constraints and conduct validations to ensure that feasible solutions are valid ones.

4.2.3 User Constraint. TinyLink first *preprocesses* the application code and infers the user requirement U. User constraints are automatically generated:

$$\sum_{i \in \{M \cup S \cup P\}} f_i^u d_i \geq 1, \quad \forall u \in U. \tag{2}$$

Example. We revisit the example shown in Figure 2. Also assume the hardware database is shown in Table 1. TinyLink automatically infers U as U = {Light, Soil_Moisture, WiFi}. Thus three user constraints are generated:

$$\begin{cases} d_7 \geq 1 & \text{(Light)} \\ d_8 + d_9 \geq 1 & \text{(Soil\_Moisture)} \\ d_2 + d_5 + d_{11} + d_{12} \geq 1 & \text{(WiFi).} \end{cases}$$

4.2.4 Hardware Constraint. While the user constraints are fairly simple, the hardware constraints are much more complicated. Due to the space limitation, we describe three important constraints.

(1) ***Port Constraint.*** TinyLink allows the use of shields to extend the capability of the mainboard. As such, for a particular type, the number of ports provided by the mainboard plus the number of ports provided by the shield, minus the number of ports consumed by the shield, should be no smaller than the number of ports consumed by the peripherals. The port constraint for TinyLink is shown below:

$$\sum_{i \in M} NO_i^+(t) d_i + \sum_{i \in S} (NO_i^+(t) d_i - NO_i^-(t) d_i) \geq \sum_{i \in P} NO_i^-(t) d_i, \forall t \in T. \tag{3}$$

(2) ***Physical Pin Constraint.*** TinyLink allows connections via physical pins. Similar to the port constraint, the physical pin constraint for TinyLink is shown below:

$$\sum_{i \in M} NI_i^+(t)d_i + \sum_{i \in S}(NI_i^+(t)d_i - NI_i^-(t)d_i) \geq \sum_{i \in P} NI_i^-(t)d_i, \quad \forall t \in T. \tag{4}$$

(3) ***MCU Pin Constraint.*** Nevertheless, the actual number of *usable* ports and physical pins is not as easy as calculating their sum. This is because some ports and physical pins are mapped to the same MCU pins, which means that they actually share the same interface and will interfere with each other if they are used simultaneously. For example, in Figure 6, the UART physical pin RX in the pin header and the pin inside the UART port (i.e., RX pin of the UART port) are *wiring* to the same MCU pin URXD on MT2502A, the SoC of LinkIt One. It is the same case for the UART physical pin TX and the TX pin in the UART port.

As a result, we need to constrain the number of usable interfaces at the MCU pin level. The total number of consumed MCU pins should be no larger than the total number of provided ones. The MCU pin constraint is generated as follows:

$$\sum_{i \in M} NM_i^+(t)d_i + \sum_{i \in S}(NM_i^+(t)d_i - NM_i^-(t)d_i) \geq \sum_{i \in P} NM_i^-(t)d_i, \quad \forall t \in T. \tag{5}$$

Example. We revisit the example in Figure 2. TinyLink generates the following constraints:

$$\begin{cases} 0d_1 + 0d_2 + 2d_3 + 0d_4 + (1d_5 + 2d_6 - 0d_5 - 0d_6) \geq \\ \quad d_7 + 0d_8 + d_9 + 0d_10 + 0d_11 + 0d_{12} \quad \text{(Port Cons. for Analog)}, \\ 0d_1 + d_2 + d_3 + 0d_4 + (0d_5 + d_6 - 0d_5 - 0d_6) \geq \\ \quad 0d_7 + 0d_8 + 0d_9 + 0d_10 + 0d_11 + d_{12} \quad \text{(Port Cons. for UART)}, \\ 6d_1 + 3d_2 + 0d_3 + 0d_4 + (6d_5 + 6d_6 - 6d_5 - 6d_6) \geq \\ \quad 0d_7 + d_8 + 0d_9 + 0d_10 + 0d_11 + 0d_{12} \quad \text{(PHY Pin Cons. for Analog)}, \\ 2d_1 + 2d_2 + 0d_3 + 2d_4 + (2d_5 + 2d_6 - 2d_5 - 2d_6) \geq \\ \quad 0d_7 + 0d_8 + 0d_9 + 0d_10 + 2d_11 + 0d_{12} \quad \text{(PHY Pin Cons. for UART)}, \\ 6d_1 + 3d_2 + 4d_3 + 0d_4 + (0d_5 + 0d_6 - 0d_5 - 0d_6) \geq \\ \quad 2d_7 + d_8 + 2d_9 + 0d_10 + 0d_11 + 0d_{12} \quad \text{(MCU Pin Cons. for Analog)}, \\ 2d_1 + 2d_2 + 2d_3 + 2d_4 + (0d_5 + 0d_6 - 2d_5 - 0d_6) \geq \\ \quad 0d_7 + 0d_8 + 0d_9 + 0d_10 + 2d_11 + 2d_{12} \quad \text{(MCU Pin Cons. for UART)}. \end{cases}$$

Together with the mainboard constraint (i.e., $d_1 + d_2 + d_3 + d_4 = 1$) and user constraints in Section 4.2.3, we can get 19 feasible sets.

Comparison with CodeFirst. The CodeFirst [24] (1) does not allow the use of shield; (2) does not allow connections via pins; and (3) does not consider the MCU pin constraints.

With the following port constraints,

$$\sum_{i \in M} NO_i^+(t)d_i \geq \sum_{i \in P} NO_i^-(t)d_i, \quad \forall t \in T,$$

CodeFirst generates the following concrete constraints for the example shown in Figure 2:

$$\begin{cases} 2d_3 \geq d_7 + 0d_8 + d_9 + 0d_{10} + 0d_{11} + 0d_{12} \quad \text{(Port Cons. for Analog)}, \\ d_3 \geq 0d_7 + 0d_8 + 0d_9 + 0d_{10} + 0d_{11} + d_{12} \quad \text{(Port Cons. for UART)}. \end{cases}$$

Assuming a fixed mainboard of BetaBlocks, CodeFirst gets only one feasible solution $\{3, 7, 9, 12\}$, which is included in the set of TinyLink's feasible solutions.

Figure 7 shows the solution space of TinyLink and CodeFirst. Under the three constraints we have described, the set of all CodeFirst feasible solutions is a subset of TinyLink feasible solutions. The search space of TinyLink is much larger since it allows complex connections between components.

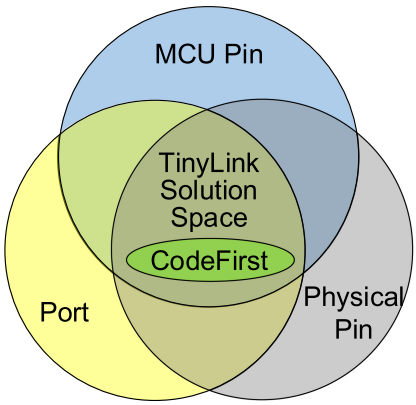


Fig. 7. Solution space comparison between TinyLink and CodeFirst.

4.2.5 Generation Process. The generation of hardware configuration consists of three main steps.

First, we solve the optimization problem described above and look for the most appropriate hardware components. In real implementations, we use a complete set of constraints listed in Table 2. We further consider the compatibility constraint. The compatibility constraints mainly consist of two categories:

(1) ***Physical compatibility constraints.*** TinyLink forbids physically incompatible hardware components to be connected, e.g., Base Shield V1.3 and Raspberry Pi 2 are not physically compatible due to their different form factors.

(2) ***Functional compatibility constraints.*** TinyLink also forbids functional incompatible hardware components to be connected with each other. For example, a Grove Temperature and Humidity Sensor Pro frequently fails to be read on a LinkIt One mainboard due to the lack of peripheral driver though their connection via ports is valid.

Both the physical and functional compatibility constraints can be formulated as follows:

$$d_i + d_j \leq 1, \text{if device } i \text{ and device } j \text{ are incompatible with each other,} \tag{6}$$

which means the final generated hardware configuration should use at most one device.

Example. We revisit the example in Figure 2. TinyLink generates the following constraints:

$$\begin{cases} d_4 + d_6 \leq 1 & \text{(physical compatibility constraints),} \\ d_2 + d_{10} \leq 1 & \text{(functional compatibility constraints).} \end{cases}$$

The first inequality indicates d_4 (Raspberry Pi 2 mainboard) and d_6 (Base Shield V1.3) should not be selected at the same time because they are physically incompatible. The second inequality indicates d_2 (LinkIt One mainboard) and d_{10} (Grove Temperature and Humidity Sensor Pro) should not be selected simultaneously in the final hardware configuration because they are functionally incompatible.

The compatibility constraints, together with the user and hardware constraints in Sections 4.2.3 and 4.2.4, constitute all the linear constraints in the optimization problem. Since the optimization problem is a classical integer linear programming problem, we utilize the open-source ILP solver `lp_solve` [18] to solve it. The `lp_solve` solver employs a branch-and-bounding algorithm to solve this optimization problem efficiently.

Second, TinyLink will show developers how to assemble these hardware components after generating the hardware component list. The connection is generated by correctly allocating

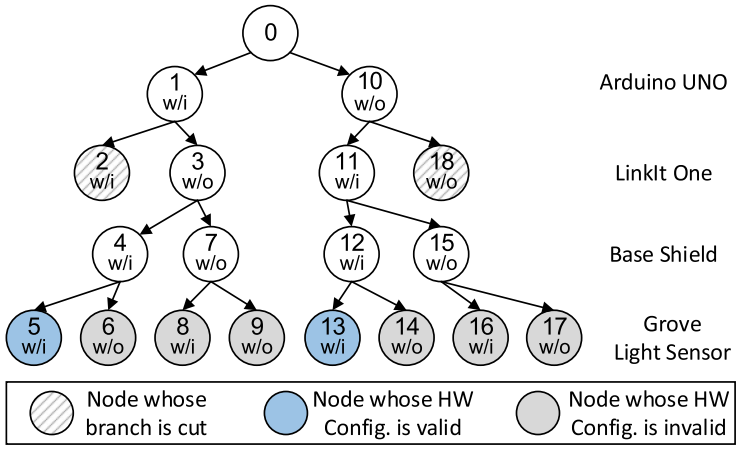


Fig. 8. The binary tree example of all hardware configurations.

interfaces on the mainboard and the shields to hardware components. Given the selected mainboard and shields, TinyLink calculates all the available interfaces, and then allocates them by priority. First, TinyLink allocates the pin interfaces occupied by built-in modules on mainboards and shields, e.g., UART pins on WiFi Shield V2.0. Afterward, TinyLink allocates non-occupied ports and non-occupied physical pins to peripherals, because ports usually occupy consecutive MCU pins shared with physical pins. Based on the allocation, TinyLink utilizes OpenCV to generate a simple visualization for the generated hardware configuration, e.g., Figure 3 visualizes the recommended hardware configuration for the application code shown in Figure 2.

Finally, TinyLink employs an additional validation procedure to verify that the recommended hardware configuration is a valid one, according to definitions described in Section 4.2.1. If the hardware configuration happens to be invalid due to invalid connections (which is rare from our experience), TinyLink invokes the ILP solver again to seek a different solution which is valid by our definition. In the future, we would like to borrow the crowdsourcing idea for IoT application development. If the current developer selects a hardware configuration that was used and reported successfully by others, the developer has a high chance of getting the correct one.

It is worth noting that TinyLink also provides additional valid hardware configurations by implementing the recommendation system. Developers may have various demands besides prices, e.g., more non-occupied interfaces for further extensions, higher CPU clock speed, larger flash and RAM, and so forth. Therefore, TinyLink lists all valid hardware configurations with the features mentioned above (e.g., number of non-occupied interfaces, CPU clock speed). TinyLink first builds a binary tree to enumerate all of them. For example, we intend to sample ambient light using four hardware components: Arduino UNO, LinkIt One, Base Shield, and Grove Light Sensor. Figure 8 shows the binary tree where each node is an indicator of the existence of a hardware component and each leaf node denotes a hardware configuration. Then TinyLink uses the pre-order traversal and adopts a branch-and-cut method [35] to accelerate the process. TinyLink checks whether a node is valid using the aforementioned ILP solver and cuts the branch if the node's hardware configuration is invalid (e.g., nodes 2 and 18 in Figure 8). Finally, TinyLink outputs all valid hardware configurations ordered by features.

5 SOFTWARE GENERATION SYSTEM

This section describes how to generate a hardware-dependent binary program from the application code. Section 5.1 describes the generation of a hardware configuration header file. Section 5.2 and

```
1  #include "TL_DeviceID.h"
2
3  #define MAINBOARD ARDUINO_UNO
4  #define WIFI ESP8266_ESP01
5  #define LIGHT GROVE_LIGHT
6  #define SOIL_MOISTURE SOIL_MOISTURE_ANALOG
7
8  #define WIFI_UART_RX 1
9  #define WIFI_UART_TX 0
10 #define LIGHT_ANALOG_OUTPUT A0
11 #define SOIL_MOISTURE_ANALOG_OUTPUT A2
```

Fig. 9. Hardware configuration header file.

Section 5.3 present TinyLink API design and the library implementations in detail. Section 5.4 describes the cross compilers, followed by Section 5.5 which discusses interactive debugging in TinyLink.

5.1 Hardware Configuration Header File

From the perspective of developers, the application code is hardware-independent. However, from the perspective of cross-compilers, the code should be hardware-dependent, e.g., link to the correct libraries corresponding to the underlying hardware. Therefore, we translate the hardware configuration information (see Figure 3) to the hardware configuration header file in C language (see Figure 9).

The hardware configuration header file is composed of three sections. The first section includes other important header files (line 1), such as the device ID header file. The second section describes which hardware components are used via macros (lines 3–6). In each line, an abstract component (e.g., `MAINBOARD` in line 3) is defined by a specific hardware component (e.g., `ARDUINO_UNO` in line 3), which relates the hardware-independent functionality to the hardware-dependent components. The third section describes the hardware connection information (lines 8–11). This hardware configuration header file is generated by the hardware generation system and is essential for compiling the application code for the target platform.

5.2 API Design

Unlike traditional IoT programming, programming with TinyLink is hardware-independent, i.e., the developers are unaware of the underlying hardware components. APIs play an important role in relating high-level semantics to low-level details. TinyLink provides generalized APIs to facilitate application programming.

In order to provide developers with widely used APIs, we investigate 116 projects from popular IoT online forums [2, 9] and websites [3, 4]. We extract 225 commonly used APIs from them and group them into 39 categories by the functionalities they provide. As shown in Figure 10, we list the 20 most-used categories and their call frequency, where the most popular one is the LED, accounting for about 23%. In the current implementation of TinyLink, we encapsulate and implement 24 categories, covering 89.78% of the total APIs we have investigated. The remaining 10.22% (i.e., uncovered) of the APIs are left unimplemented, including those controlling DIY devices, transmitting and receiving infrared signals, and so forth. Given a limited development time, we have decided to implement the most important and commonly used APIs while skipping those infrequently invoked ones.

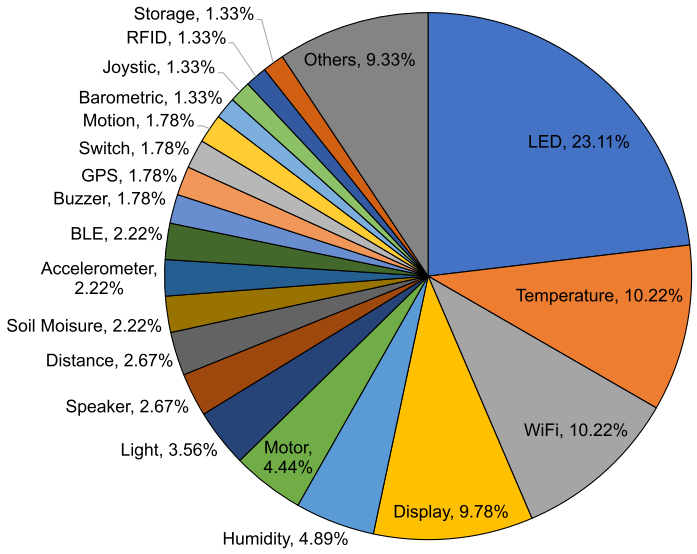


Fig. 10. API call frequency summarized from real-world projects.

We say that TinyLink supports a project if all the APIs used in this project have corresponding TinyLink APIs. 67.24% of the projects are supported by TinyLink and can be ported to TinyLink with little modifications. The remaining 32.76% of the projects have at least one uncovered API and thus cannot be easily ported to TinyLink in the current stage. We plan to implement more TinyLink APIs to support more IoT applications in the future.

How to exchange messages over unreliable networks in an energy-efficient manner is an important issue in IoT development. Message Queue Telemetry Transport (MQTT) protocol is a lightweight messaging protocol [13] which builds on top of the TCP protocol. It has been adopted as a primary protocol for IoT communications by major IoT cloud providers (e.g., IBM, Amazon, and Microsoft). To support this widely used protocol in IoT development, we provide MQTT APIs in TinyLink. Once a TCP connection is established, a TinyLink node with MQTT can connect to a broker (i.e., MQTT client at the server side) upon it, and then publish/subscribe their information. We have tested our TinyLink MQTT APIs on IBM Bluemix and China Mobile IoT Open Platform. All four mainboards, i.e., Arduino UNO, LinkIt One, Raspberry Pi 2, and BeagleBone Black, can connect to MQTT brokers of the two cloud platforms using the ESP8266 WiFi module and the Grove UART WiFi module, as well as the built-in WiFi module of LinkIt One and the built-in Ethernet modules of Raspberry Pi 2 and BeagleBone Black.

In addition, we provide basic debugging APIs for developers. They can write `REQUIRE DBGPrint` to indicate that they require printing out debugging information. In this case, the TinyLink hardware system will occupy an additional serial interface on the mainboard. All debugging information will be transmitted via this serial interface. Developers can use `TL_Debug.print()` to print out their own debugging information.

5.3 Library Implementation

Libraries are the actual implementations of TinyLink APIs. We are facing practical implementation challenges since each library implementation requires developing efforts and the number of required implementations may grow rapidly with an increasing number of hardware components. We address these challenges in the following ways.

```
void TL_LED::turnOn() {
    pinMode(LED_DIGITAL_OUTPUT, OUTPUT);
    digitalWrite(LED_DIGITAL_OUTPUT, HIGH);
}
```

Fig. 11. Glue code example of implementing an LED function.

First, we implement the most commonly used libraries according to our experience so that we can benefit a greater number of users given limited development time. With the increasing use of TinyLink, we could get more feedbacks about which libraries should be implemented with a higher priority.

Second, we try to reuse existing libraries and only add *glue* code to implement TinyLink APIs. Writing glue code includes abstracting the unified input/output interfaces, replacing the hardware-dependent code with macros, adding conditional syntax in the API header file and so on.

Figure 11 illustrates how we implement the TinyLink API `TL_LED.turnOn()` by reusing libraries on four mainboards. For these four mainboards, we use the function `pinMode()` to configure LED pin behavior and use `digitalWrite()` to turn the LED on. These APIs are implemented differently for different platforms. On Arduino and LinkIt platforms (Arduino programming environment and VM on Linux), they can be easily implemented using the system library. On Raspberry Pi and BeagleBone platforms (Debian-based Linux operation systems), they can be implemented using third-party libraries, e.g., wiringPi [26] and wiringBone [17]. The implementation overhead for glue code is relatively small when we carefully choose the existing libraries.

Finally, we will allow for crowdsourcing the library implementations by application developers. We will release TinyLink libraries to be open source online, and in the long term, we hope that more and more IoT developers will join us to implement the useful libraries which can be shared among other developers. As an initial effort, we provide component templates written in C++ for developers to implement TinyLink libraries for a new hardware component. We roughly divide TinyLink libraries into four categories, system libraries, communication libraries, sensor libraries, and actuator libraries. We provide developers with a category menu to help them locate which component templates they can use. For example, to implement a library for a simple sensor, a developer can use the sensor template we have developed, inherit the `Sensor` class, and implement abstract interfaces like `virtual int _read()=0`. If a developer intends to implement libraries for a new mainboard, we provide basic templates in system libraries such as serial template, timer template, and so forth.

Furthermore, if the new library has corresponding new hardware to be added to the TinyLink system, the extending process is a little more complicated. Besides implementing the software APIs, the detailed hardware information such as the price, and the number of pins and ports are also required to be added into the hardware database.

It is also worth noting that it is possible for TinyLink to generate a hardware configuration which misses some software implementations. To address this issue, we provide two options for the developers: (1) provide the best IoT hardware configuration and the application developers have to implement the required library code; and (2) provide the suboptimal solution with complete software implementations.

5.4 Cross-Compiler

The preprocessed code needs to be cross-compiled on the cloud to the binary code for the target platform. There are two key problems that TinyLink needs to address: (1) which libraries to link and (2) which cross-compiler to use. TinyLink relies on a header file `TL_Config.h` which encodes the

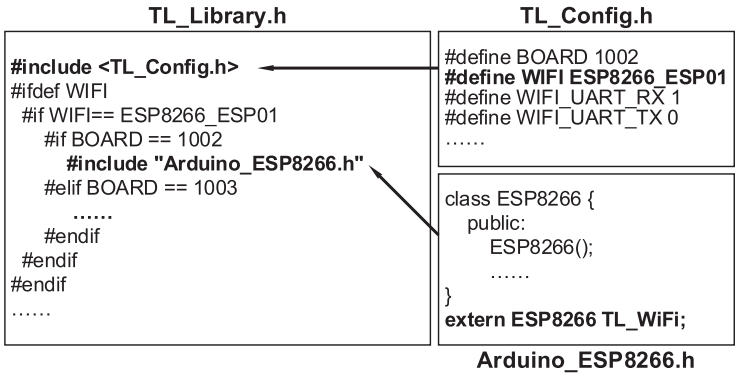


Fig. 12. Including libraries using header files.

Table 3. Cross-Compilers of Four Mainboards

Mainboard	MCU Architecture	Cross Compiler
Arduino UNO	AVR ATmega	avr-gcc, avr-g++
LinkIt One	ARM7 EJ-S	arm-none-eabi-gcc, arm-none-eabi-g++
Raspberry Pi 2	ARM Cortex-A7	arm-linux-gnueabihf-gcc, arm-linux-gnueabihf-g++
BeagleBone Black	ARM Cortex-A8	

hardware configuration. The type of mainboards defined in `TL_Config.h` determines the specific cross-compiler.

Figure 12 shows how hardware-independent application code and hardware-dependent libraries are linked. TinyLink libraries include two headers files, `TL_Library.h` and `<mainboard>_<peripheral>.h`, for transforming hardware-independent APIs to hardware-dependent APIs. For the example shown in Figure 12, `TL_Library.h` will include `TL_Config.h` to include necessary function modules, e.g., `ESP8266_ESP01`, which again includes `Arduino_ESP8266.h` according to the hardware configuration defined in `TL_Config.h`.

We list cross-compilers for four mainboards in Table 3. The Arduino UNO based on AVR ATmega utilizes avr-gcc and avr-g++ compilers. LinkIt One, which is based on ARM7, leverages arm-none-eabi-gcc and arm-none-eabi-g++ compilers. The Raspberry Pi 2 and BeagleBone Black, with ARM Cortex-A7 and Cortex-A8, respectively, both use arm-linux-gnueabihf-gcc and arm-linux-gnueabihf-g++ compilers.

5.5 Interactive Debugging

TinyLink supports interactive debugging if the native system supports it. In the current stage, TinyLink supports interactive debugging using gdb for the Debian systems on Raspberry Pi and BeagleBone Black. If gdb debugging is required by writing `REQUIRE GDB`, TinyLink will compile the application code to include necessary debugging information. In addition, developers are provided with the source code of the whole project, including high-level application code as well as low-level hardware-dependent library code. Based on these, developers can log into the platform and debug the source code with functions provided by gdb, e.g., breakpoints, watchpoints, and stepped execution.

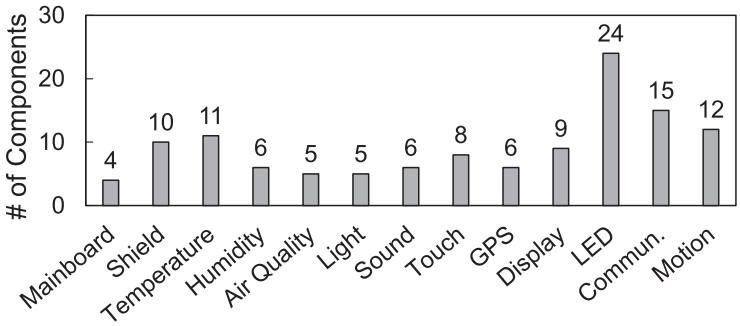


Fig. 13. Number of components in TinyLink database.

5.6 IDE Integration

TinyLink is a holistic system that includes a cloud-based compiling architecture and Web-based application programming interfaces encapsulated as RESTful APIs. With these, TinyLink enables developers to program in a lightweight local development environment. Currently, TinyLink provides two kinds of integrations: one with local IDE and another with cloud IDE. For the former one, TinyLink supplies a customized extension of the Visual Studio (VS) Code, a free, open-source local IDE developed by Microsoft. Developers can complete the development process within the VS code and even interactively debug in it. For the latter one, TinyLink supplies developers with a cloud IDE powered by Theia [10] and several customized plugins which facilitate all TinyLink functions. Developers only need a browser and can start programming.

6 EVALUATION

In this section, we present the evaluation of TinyLink. Section 6.1 presents the experiment setup. Section 6.2 shows the overall evaluations in terms of ease of programming, feasible solutions, and overhead. We study four real-world cases using both TinyLink and CodeFirst [24] in Section 6.3. Section 6.4 shows a user study of 28 undergraduate students.

6.1 Experiment Setup

Hardware Component. In Figure 13, we list the number of components in our hardware database grouped by functionalities. There are 4 mainboards, 10 shields, and more than 100 peripherals recorded in our database. The four mainboards include Arduino UNO (UNO for short), LinkIt ONE (ONE for short), Raspberry Pi 2 (RP2 for short), and BeagleBone Black (BBB for short). The characteristics (e.g., resolution and sensing range) of these components are also stored in our database.

Benchmark. We use six frequently used benchmarks according to Figure 10 for evaluation, which are (1) LED Write (LED for short), which turns on an LED; (2) WiFi GET (WiFi for short), which sends an HTTP GET request to a website in the local area network and retrieves the response; (3) File Write & Read (File for short), which writes data to a file on a storage module and then reads the data; (4) Temperature Read (Temp for short), which reads temperature data from a sensor; (5) Humidity Read (Humi for short), similar to Temp; and (6) Light Read (Light for short), similar to Temp.

Case Study. We use four real-world case studies, an indoor smart houseplant node described in Section 2, an air quality monitoring node, two Blink-to-Radio LoRa [15] nodes, and a voice controlled LED lamp node. More details are presented in Section 6.3.

User Study. Participants are required to implement 11 pre-defined cases that can be divided into four difficulty levels. Level one includes cases 1–2, which include LED blinking and printing

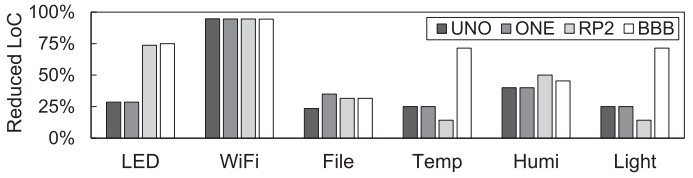


Fig. 14. Percentage of reduced lines of code.

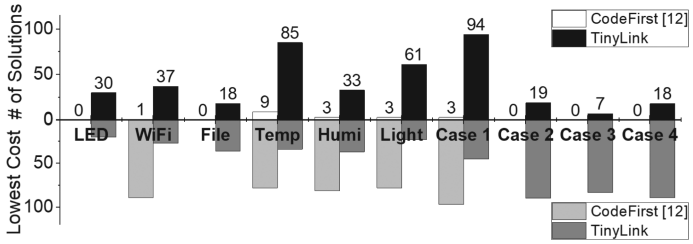


Fig. 15. Number of solutions and the lowest cost.

to serial. Level two includes cases 3–5, which include sensing temperature, writing to SD card, and getting data from Internet via WiFi. Level three includes cases 6–8, which include posting different indoor environment data to the TinyLink cloud, and making LED blink if the data exceeds thresholds. Level four includes cases 9–11, which include the smart houseplant case and the air quality cases in both local storage and cloud mode. More details are presented in Section 6.4.

6.2 Overall Evaluation

6.2.1 Ease of Programming. First, we compare lines of code needed to implement the benchmarks between using TinyLink APIs and using original APIs (e.g., APIs provided by hardware manufacturers). We implement the six benchmarks on four mainboards and report the reduced lines of code. In Figure 14, we can see that using TinyLink reduces the lines of code by 14.29%–94.67%. The average percentage of reduced lines of code on four mainboards is 52.58%. In particular, for implementing the WiFi GET benchmark, using TinyLink APIs reduces more than 94.40% of lines of code on all mainboards. This is due to the simple API design and a large amount of glue code implementations for the WiFi library.

Second, we compare the lines of code between TinyLink and CodeFirst [24]. CodeFirst uses 27 lines of code to implement an example of reading data from a temperature sensor, displaying data on an LCD screen, and transmitting data via Bluetooth. This is the only example which has the source code in CodeFirst. In TinyLink, developers can implement an application with the same functionalities only using 15 lines of code.

6.2.2 Feasible Solution. TinyLink can generate many feasible solutions after exploring the hardware database and choose the best one according to the given optimization criterion (e.g., the total cost). A larger searching space will provide more opportunities to generate more feasible solutions, as well as a better solution. We evaluate the feasible solutions for six small benchmarks and four case studies, and compare the results with CodeFirst [24]. Figure 15 shows the results. For each benchmark and case study, we count the number of feasible solutions, as well as the lowest cost in the set of feasible solutions. We can observe that TinyLink generates far more feasible solutions than CodeFirst and much lower total cost for each benchmark and case study. In the LED write and the File Write & Read benchmarks, CodeFirst fails to generate any feasible

Table 4. Relative Execution Overhead

API From Benchmark	LED Write	UART Write	UART Read	File Write	File Read	Temp Read	Humi Read	Light Read
UNO	13.79%	0.00%	0.00%	1.10%	1.26%	0.01%	0.01%	7.56%
ONE	6.25%	0.02%	0.63%	0.38%	0.48%	0.02%	0.04%	1.15%
BBB	10.86%	0.76%	2.73%	15.68%	14.16%	0.03%	0.04%	8.90%
RP2	12.86%	10.74%	7.50%	0.71%	1.94%	0.43%	0.48%	2.13%

Table 5. Program Space Overhead (Bytes)

Benchmark	LED	WiFi	File	Temp	Humi	Light
UNO	166	184	2178	374	278	414
ONE	4372	2780	31000	3328	3320	3636
BBB	78224	63668	82311	79428	79428	77504
RP2	30713	11039	33317	27016	27016	26332

solutions, because it only uses ports which are usually not supported by peripherals with the storage functionality.

6.2.3 Overhead. The implementations of glue code on existing libraries introduce overhead to the generated IoT applications. In the following, we evaluate the execution overhead, program space overhead, and memory space overhead.

Execution Overhead. Most implementations of unified TinyLink APIs are the encapsulations of existing ones, and the overhead comes from the glue code. We take experiments on the execution time of API calls in our benchmarks. Table 4 shows the relative execution overhead of using TinyLink APIs compared with using original APIs. Considering the magnitude of the execution overhead is μs (e.g., 0.75 μs for the LED benchmark on UNO), the overhead is acceptable. We can see high overhead on some platforms. This is because the native APIs execute very fast on these platforms. On the other hand, the wrapping overhead of TinyLink is roughly constant: it is mainly incurred by the function calling overhead, e.g., pushing the function arguments to the stack or other calling conventions. For example, the execution time of the native humidity read and light read API on the BBB platform are 525.4 μs and 23.49 μs, respectively. Hence the relative overhead percentage of light read API is much higher than that of humidity read. We can also see very small overhead because the wrapping overhead can be *negligible for some optimized implementations*. For example, the wrapping of `TL_Serial.write()` on UNO is implemented as a C++ macro instead of the typical method of function calls. Hence, `TL_Serial.write()` exhibits almost no overhead on UNO.

Program Space Overhead. The program space overhead is proportional to the amount of implemented glue code. Due to different MCU architectures, we use different methods to measure the program space. For the UNO with an AVR MCU, the program space is calculated by the sum of `.text` and `.data` segments. For the other three with ARM MCU, the program space is the size of their cross-compiled binary programs.

Table 5 shows the program space overhead. The program space overhead of UNO and ONE is no more than 3 KB and 31 KB, respectively. Considering their program flashes are 32 KB and 16 MB, respectively, the overhead is small and acceptable. The reasons why the overhead of BBB and RP2 is much larger is that they run on a Debian Linux system and their binary programs are in ELF format. But considering their program flashes are at least 4 GB, the overhead within 100 KB is negligible.

Table 6. Memory Space Overhead (Bytes)

Benchmark	LED	WiFi	File	Temp	Humi	Light
UNO	21	170	56	23	23	23
ONE	1272	1384	21384	1200	1208	1248
BBB	82591	99511	85193	82756	82627	82257
RP2	30713	11039	33317	27016	27016	26332

Table 7. Hardware Configurations of Smart Houseplant Nodes

	TinyLink	CodeFirst [12]
Mainboard	Arduino UNO	BetaBlocks
Shield	Base Shield V1.3	-
Peripheral	Grove Light Sensor	Grove Light Sensor
	Soil Moisture Analog Sensor	Grove Moisture Sensor
	ESP8266 ESP01 WiFi Module	Grove UART WiFi Module
Total Cost	$44.72	$96.70

Memory Space Overhead. The measured memory space overhead is composed of the overhead from static memory overhead (i.e., `.text`, `.data`.) and runtime memory overhead (i.e., stack and heap). Table 6 shows that the memory space overhead is small for UNO and is negligible for the other three. For UNO, the overhead of all benchmarks is within 171 B, 8.35% of its RAM size (i.e., 2 KB). For ONE, the overhead of all benchmarks is within 21 KB, 1.03% of its RAM size (i.e., 2 MB). For BBB and RP2, the overhead of benchmarks is within 100 KB, which is negligible since their RAM is 512 MB and 1 GB, respectively.

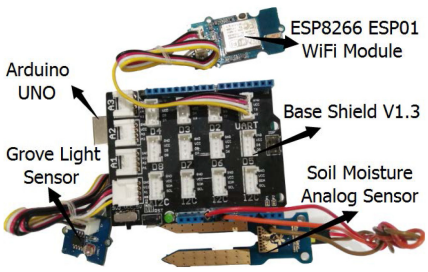
6.3 Case Study

Smart Houseplant Node. This case has been described in Section 2. Figure 2 shows the application code. Under the criterion of the lowest cost, the best hardware configurations for both TinyLink and CodeFirst [24] are shown in Table 7. In the TinyLink solution, the Base Shield V1.3 is selected, because it can provide ports (required by the Grove Light Sensor) which UNO does not contain. The fixed platform of CodeFirst, BetaBlocks, contains ports so that it does not need shields. It is obvious that the cost of TinyLink's solution is much lower than the cost of CodeFirst's solution. This is because BetaBlocks's characteristic of only using ports limits the searching space for feasible solutions. The assembled node of TinyLink is shown in Figure 16(a).

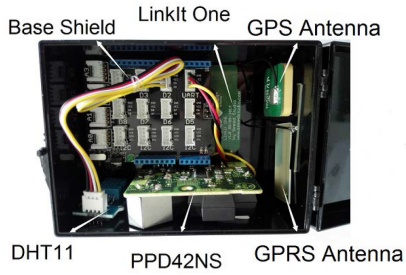
Air Quality Node. Mosaic is a mobile sensor network system for city-scale sensing [20]. The requirement of a mosaic node is measuring PM2.5, PM10, position, temperature, and humidity every 30 seconds. Then the sampled data are uploaded to a cloud server via GPRS. In addition, output log data are stored in the SD card for further debugging and developing.

We intend to build such nodes using both TinyLink and CodeFirst. The generated hardware configurations are shown in Table 8. Mosaic Node V1 is the original node used in [20], which is very expensive. TinyLink generates a hardware configuration that reduces about 41% of the total cost, due to the built-in components on LinkIt One. In Table 9, we can observe that TinyLink achieves all functionalities provided by Mosaic Node V1. CodeFirst cannot generate a feasible solution since there are no suitable interfaces for storage modules. The assembled node of TinyLink is shown in Figure 16(b).

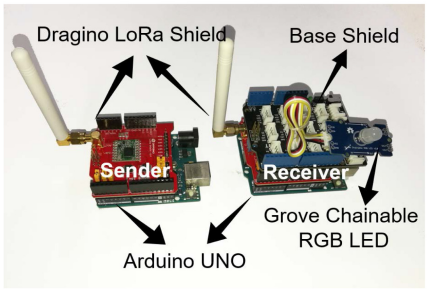
Blink-to-Radio LoRa Nodes. TinyLink enables developers to build IoT applications which have interactions across nodes such as the well-known Blink-To-Radio in TinyOS [34] by implementing multiple pieces of application code. In this simple case, we intend to send one-shot blink commands periodically from the sender to the receiver via LoRa [15], which supports long-range



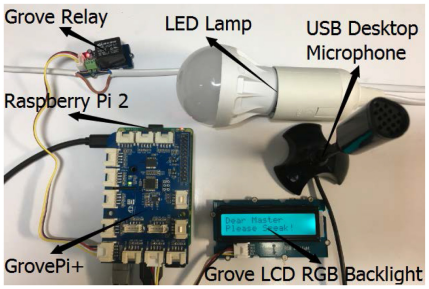
(a) Smart Houseplant Node.



(b) Air Quality Node.



(c) Blink-to-Radio LoRa Nodes.



(d) Voice Controlled LED Lamp Node.

Fig. 16. Assembled TinyLink nodes for four real-world case studies.

Table 8. Hardware Configurations of Air Quality Nodes

	TinyLink	Mosaic Node V1 [26]	CodeFirst [12]
Mainboard	LinkIt ONE	Arduino UNO	No Solutions
Shield	Base Shield V1.3	Base Shield V1.3	
	-	GPRS Shield V2.0	
	-	SD Card Shield V4	
Peripheral	Dust Sensor (PPD42NS)	Dust Sensor (PPD42NS)	
	Grove Temperature and Humidity Sensor (DHT11)	Grove Temperature and Humidity Sensor (DHT11)	
	-	Grove GPS (SIM28)	
Total Cost	$89.70	$150.99	N/A

Table 9. Functionalities of Implemented Air Quality Nodes

Functionality	TinyLink	Mosaic Node V1 [26]
PM2.5 Monitoring	✓	✓
PM10 Monitoring	✓	✓
Temperature Monitoring	✓	✓
Humidity Monitoring	✓	✓
GPS Sampling	✓	✓
Storing Data to the SD Card	✓	✓
Uploading Data to the Cloud	✓	✓
Periodically Executing Tasks	✓	✓

Table 10. Hardware Configurations of Blink-to-Radio LoRa Nodes

	TinyLink	CodeFirst [12]
Mainboard	Raspberry Pi 2	No Solutions
Shield	GrovePi+	
Peripheral	Grove Relay	
	USB Desktop Microphone	
	Grove LCD RGB Backlight	
Total Cost	$89.20	N/A

Table 11. Hardware Configurations of Voice Controlled LED Lamp Nodes

	TinyLink	CodeFirst [12]
Mainboard	Raspberry Pi 2	No Solutions
Shield	GrovePi+	
Peripheral	Grove Relay	
	USB Desktop Microphone	
	Grove LCD RGB Backlight	
Total Cost	$89.20	N/A

and low-power communications and is promoted as an infrastructure solution for IoT. The common requirement of the sender and the receiver is transmitting messages via LoRa and the receiver requires LED blinking in addition.

Table 10 shows the generated hardware configurations of both the sender and the receiver for TinyLink and Code-First, respectively. In TinyLink, the sender and the receiver both use Dragino LoRa Shields. However, the receiver uses an external LED instead of the built-in LED on Arduino UNO. This is because the LoRa Shield, which uses the SPI interface, occupies the MCU pin of the built-in LED. On the other hand, CodeFirst still cannot generate a feasible solution due to a lack of suitable interfaces. The assembled nodes of TinyLink are shown in Figure 16(c).

Voice Controlled LED Lamp Node. TinyLink is suitable for building smart home applications. We intend to control home appliances (e.g., LED lamps) via smart devices which take voice commands as input. We have implemented a voice controlled LED lamp node via TinyLink. The source code only contains 51 lines of code. The requirements extracted from the code are recording the user's voice periodically using a sampling rate of 16 kHz, recognizing voice commands (e.g., "Light On" and "Light Off"), printing commands on an LCD screen, and controlling the corresponding home appliance.

Table 11 lists the generated hardware configurations. The hardware configuration for TinyLink contains a USB desktop microphone directly attached to a USB port on a Raspberry Pi 2, a Grove relay module, and a Grove LCD RGB backlight module which are attached to ports on a shield, GrovePi+. Figure 16(d) shows the assembled node. There are no solutions for CodeFirst because its mainboard lacks interfaces for voice recording modules.

The library implementations for the recording API and the voice recognition API are based on PocketSphinx, a CMU's speaker-independent continuous speech recognition engine [31].

6.4 User Study

To evaluate TinyLink's performance, we conduct a user study on 28 undergraduate students who attend the course of computer networks. They are required to implement 11 pre-defined cases described in Section 6.1. We divide the students into 14 groups and provide each group with necessary

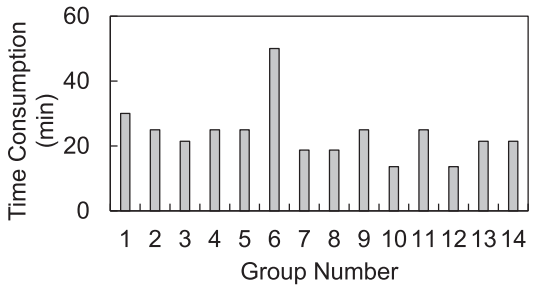


Fig. 17. Case development time on average of 14 groups.

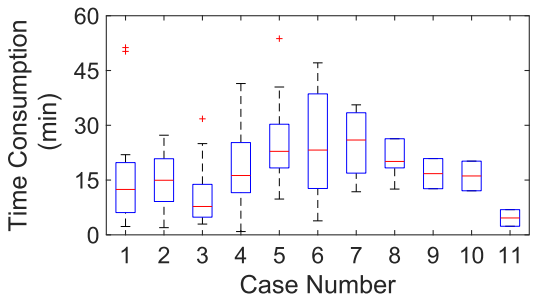


Fig. 18. Detailed development time of 111 cases.

mainboards, shields, and peripherals. We also give them a carefully designed user guide which contains three illustrative TinyLink examples; a serial example using UNO, a Blink-to-Radio example using ONE, and a sensing example using RP2, as well as complete TinyLink API references. Before the experiment, they fill out a small questionnaire about their experiences in programming. Results show that three groups are familiar with IoT programming, three groups have little experience, and eight groups have never touched this area. And three groups are very familiar with C-like languages, ten groups are quite familiar, while one group has little experience.

To obtain their development time, we record the timestamps of calling Web-based RESTful APIs and the logs of TinyLink cloud. Two groups implement all 11 cases during the $2\frac{1}{2}$ hour experiment, and all groups implement about 6.9 cases on average. Figure 17 shows the case development time on average of each group, which is about 23.86 minutes per case. This includes the complete development process from writing the code to watching the result of assembled nodes. Figure 18 shows the detailed development time of each case by all groups. From the first two easy cases, we can observe that students can quickly start developing with TinyLink. And from the last six difficult cases, their development time drops as they become familiar with TinyLink. In order to take an in-depth look, we show the timeline of group 10 who completes all 11 cases in Figure 19. It is interesting to discover that the two members both implement the first five cases to be familiar with TinyLink and try to cooperate for the rest of the cases. Their case development time on average is 17.56 minutes and 13.03 minutes, respectively. These results show that TinyLink can help developers quickly build IoT applications and can greatly accelerate the process.

7 DISCUSSION

In this section, we discuss several important open issues.

Optimization Criteria. Currently, TinyLink's optimization criterion is to minimize the cost. However, other optimization criteria (e.g., extensibility, energy consumption) can also be adopted.

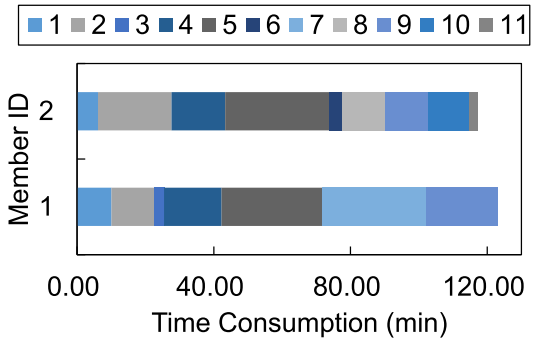


Fig. 19. Breakdown of development time of each member in group 10.

For extensibility, it is possible to define an extensibility metric as the number of unoccupied interfaces which could be used in the future. For energy consumption, however, it is a non-trivial task to estimate accurately for a particular platform during design-time given the application code. One possible approach for optimizing energy consumption is described as follows. First, we should estimate the execution time and energy consumption of each TinyLink API for different components on different platforms by well-designed benchmarks (or values reported in datasheets). Second, we should carefully analyze the application code for information such as which TinyLink APIs it has invoked. Using the above information, we can roughly estimate the energy consumption of the entire code for different components on different platforms. Finally, we can look for the platform with minimum energy consumption by setting energy consumption as an optimization criterion and other factors like the cost as constraints.

TinyLink's Extensibility. Due to TinyLink's high-level abstraction, the application code is hardware-independent. TinyLink can incorporate other MCUs by including their features into the hardware database as well as glue code for the new platforms. Therefore, other MCUs (e.g., MSP430) can also be supported by TinyLink in the future. TinyLink uses COTS hardware components and deals with the issues on how to assemble them in a compatible way. In the current stage, we think that TinyLink is primarily targeting for rapid prototyping. We think that TinyLink's approach for rapid prototyping can have important implications and guidance to the final production. TinyLink mainly focuses on the fast prototyping of IoT applications, especially for non-experts. The current implementation of TinyLink considers COTS IoT components instead of circuit-level components such as wiring, resistor, and capacity. Circuit-level development of IoT hardware (e.g., using the wiring, resistors, and capacities) is well studied in the Electronic Design Automation (EDA) community. Although TinyLink focuses on prototyping component-based IoT applications, we can also support industrial production by using the System-in-Package (SiP) technique which treats the wiring, resistor, and capacity as standalone packages and provide prototyping constraints between these packages. These constraints can be incorporated into the TinyLink optimization problem.

Code Migration. For developers who are familiar with embedded systems (especially the hardware), code transformation is indeed a good feature for porting their existing code from one platform to another. For other developers, we believe that TinyLink is a good approach since it significantly reduces the developing efforts. With TinyLink abstraction, the code is hardware-independent and is also easy to migrate between platforms with the cross-compilation on the cloud. Moreover, TinyLink reuses the Arduino programming style heavily to prevent a steep learning curve. Since code transformation is another direction of work, we will consider it as possible future work of TinyLink.

8 RELATED WORK

TinyLink borrows heavily from three large areas of prior work: hardware platform design, hardware/software co-design, and IoT rapid development. Each of these topics has made key implications which TinyLink incorporates into its design and structure.

Hardware Platform Design. With the development of MEMS technology, we have seen significant advances in the hardware industry. Early in 2003, the well-known sensor network platform, Telos, was released along with the TinyOS operating system by researchers at UC Berkeley [34].

The most important considerations for a sensor network platform are energy efficiency and small form factor. The design of such a dedicated, small platform is difficult and requires expert knowledge. For example, Dutta et al. present a building block approach [21] to hardware platform design based on a decade of collective experience, arriving at an architecture in which general-purpose modules that incorporate commonly used functionality are integrated with application-specific carriers that satisfy the unique sensing, power supply, and mechanical constraints of an application.

Andersen et al. present the design of a new hardware and software platform [14] by bringing together Mobile, Wearable, Maker, and Wireless Sensor Network technologies to achieve a high degree of synergy and energy efficiency.

Sutton et al. present a design methodology [39] for adaptive event-triggered acoustic sensing systems, with careful consideration for adaptability, responsiveness, and energy efficiency. All the work aims to design an energy-efficient hardware platform with good system performance. However, *expert knowledge* on the hardware experience and embedded software have created a barrier for upper-layer application development. TinyLink intends to remove this barrier by incorporating hardware knowledge into our system design.

Recent years have also witnessed significant innovations in the Maker domain around Arduino [1] and Raspberry Pi [8]. These platforms are characterized by powerful processors with rich interfaces. These development trends have important implications for our designs: (1) the COTS hardware components and their compositions have already enabled a wide range of innovative applications; (2) we need to carefully consider the complex connections among hardware components and the API implementations on different platforms.

Hardware and Software Co-design. Hardware/software co-design approaches use synthesis strategies to generate efficient hardware and software partitions.

The most relevant to our work is Platform Based Design (PBD) [32]. The goal of PBD is to select and compose a subset of available components (i.e., the configuration), from the design space of possible platform configurations. A good and implementable configuration satisfies the system constraints as well as all component-imposed assumptions. PBD is a meet-in-the-middle process which maps an abstracted top layer description to a more detailed lower layer implementation as well as building a platform by defining the library that allows performance estimation.

Peter et al. propose a component-based description language CoDeL [36] that allows system designers to express components as reusable building blocks of the system with parameterizable models, properties, and interconnectivity. The automatic mapping from the higher layer to the lower layer is the process of exploration of complex design spaces, which is frequently fostered by satisfiability (SAT) [16] solvers or Integer Linear Programming (ILP).

Similar to PBD, TinyLink also adopts an automatic mapping process from the application logic to a concrete hardware configuration. While PBD addresses a general problem, TinyLink addresses specific and practical challenges such as hardware-independent APIs, compatibility among COTS hardware components, and implementations of glue code on different platforms.

IoT Rapid Development. The rapid development of IoT systems has attracted much research attention from both industrial and academic communities.

Shayne Hodge proposes a general idea [29], which is to build an architecture like that of a modern web application. At a very high level in this model, the IoT hardware sends data over a network (or the Internet) to the backend software for storage and processing. The user interface is built as a web application, which allows it to be viewed on a broad range of devices. The details on how to build the IoT hardware, however, are not given.

The Matrix project [6] was launched on Kickstarter in 2015. The platform contains up to 15 sensors so that users only need to create IoT Apps, without caring about the hardware. However, the platform is fixed; it is not flexible to create customized IoT Apps.

IOTIFY [5] is the virtualization engine for the IoT to help build IoT applications. IOTIFY reduces the complexity of dealing with hardware and large networks by virtualizing IoT endpoints in the cloud. Different from IOTIFY, TinyLink generates real hardware components and application software.

.NET Gadgeteer [43] is an integrated platform from Microsoft to support developing with customized components. Developers can quickly build devices with the help of Gadgeteer modules, .NET Micro Framework, and 3D design tools. Wio Link [11] is a similar approach which builds upon the Wio Link board. TinyLink focuses on how to rapidly develop IoT applications using a variety of COTS components, instead of using customized components.

Flicker [28] is a rapid prototyping system for batteryless devices, TinyLink focuses not only on batteryless ones but also on other general IoT hardware.

LibAS [41] is a cross-platform framework that enables rapid development of mobile acoustic sensing Apps. Its framework hides a large amount of engineering efforts from developers by providing platform control components which encapsulate the underlying details. Developers can only focus on implementing essential sensing algorithms. Different from LibAS, TinyLink focuses on development in IoT scenarios and faces unique challenges like the hardware configuration generation.

Another synthesizing system, EDG [38], suffers from high synthesis time. For example, it takes 187.88 minutes at most to synthesis under a database with 73 devices. The ILP formulation for hardware and user constraints of TinyLink exhibits a much more efficient synthesis performance.

A recent approach is the code-first design to prototype wearable devices [24]. The hardware configuration would be generated from the analysis of the application code, because one software module is directly mapped to one hardware component and hardware dependencies can be determined by analyzing software dependencies. However, it assumes a fixed mainboard, limiting its capability to embrace a diverse set of COTS components. Moreover, another software-oriented synthesizing system, Esperanto [33], also only supports two kinds of IoT devices, which limits its usage.

The design of TinyLink is much more complicated since it supports different mainboards and provides pin-level abstractions with careful consideration for shields. TinyLink also includes software libraries to facilitate upper layer application programming.

9 CONCLUSION

In this article, we present TinyLink, a holistic system for rapid development of IoT applications. TinyLink uses a top-down approach for both hardware and software designs. Developers only need to specify key application logic with TinyLink APIs, without dealing with the underlying hardware. TinyLink takes their code as input, and automatically generates the hardware configuration and the binary program executable on the target platform. We implement TinyLink and evaluate its performance using benchmarks, four real-world case studies, and one user study.

Results show that TinyLink achieves rapid development of IoT applications, reducing 52.58% of lines of code on average for implementations while incurring acceptable overhead.

The future work of TinyLink includes two directions. First, we will further extend the supported hardware components of TinyLink. Second, we will extend TinyLink to other optimization goals, e.g., energy, performance, and extensibility.

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