Electric Current Based Power Line Communication for Plug-Load Device Auto Identification

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Abstract—A smart building has an outlet-level power meters for managing the energy consumption of plug-load devices – the devices or appliances connected to the outlets. Identification of the connected devices used to be made by system operators in the traditional building energy management systems (BEMS), but it is no more realistic for such fine-grained power monitoring applications. This paper proposes a new communication method – electric current based power line communication (ECPLC), which enables automatic identification of plug-load devices without the intervention of system operators. Using ECPLC, a device transmits bit sequences that show its identifier on the electric current flow, which propagates only to the outlet from the connected device. We have designed a transmitter and a receiver of ECPLC with studying the electric model that enables the communication. We have also implemented them, and carried out experiments on varieties of cases. The results show that ECPLC performs very well in typical application scenarios, indicating that it is useful for automatic identification of plug-load devices.

Keywords—*Power Line Communication, Smart Buildings, Building Energy Management System.*

I. Introduction

A smart building has outlet-level power meters to allow fine-grained monitoring of energy consumption of devices or appliances – which are called "plug-load devices" in this paper. Smart building needs identification of the plug-load devices connected to the outlets to manage the consumption. Building operators used to put the connection information by hand in a traditional building energy management system (BEMS), however this approach reaches the limit. Some devices are portable, which may connect to any outlets and BEMS cannot follow the change without intervention of the building operators.

Automatic identification of plug-load devices is necessary to outlet-level energy management. Inspired by the works of non-intrusive load monitoring (NILM[10][12]), researchers have studied on the "features" of energy consumption [3][9] (*i.e.,* pattern of energy usage), trying to identify the device connected to the outlet. We call this approach as passive scheme. Passive approach can estimate the types of the devices by the observation of the energy consumption. However, the approach cannot easily "identify" the device itself if they have many similar devices. Active identification schemes are probably essential so as to precisely perform auto identification in such a scenario.

In this paper, we propose a new power line communication, named electric current based power line communication (ECPLC). ECPLC can transmit bit sequences using "electric current", which propagates on a closed circuit – making a loop. In the proposal, each device periodically transmits its identifier on its power line, and the outlet can receive the identifier of the connected device. In this way, we can achieve automatic identification of plug-load devices.

ECPLC is totally different from the well-known PLCs[1][8][7]. They transmit signals on the voltage of the power line, which we say electric voltage based PLC (EVPLC). EVPLC cannot be used due to the nature of the voltage propagation. The signals of EVPLC transmitted from a device would reach all the outlets, therefore we would not be able to identify where it is connected. The signals of ECPLC from a device will reach the sole outlet, and we can recognize that the device is connected to the outlet. The proposed ECPLC enables immediate and precise identification.

This paper focuses on the basic principles of ECPLC. We assume one-to-one (device-to-outlet) simplex communication, propose the design of the transmitter and the receiver of ECPLC and develop a signal propagation model. We have implemented the ECPLC transmitter and the receiver and evaluated the performance considering typical building deployment scenario. The following other practical works are out of focus in this paper: collision avoidance, duplex communication, design of identifiers and system implementation.

The rest of the paper is organized as follows. Section II highlights the works related to the domain of plug-load auto identification and power line communication. Section III explains the proposal, ECPLC. the ECPLC transmitter and the ECPLC receiver are also introduced. Section IV provides the evaluation of ECPLC. In Section V, we discuss the result of the experiment and lists the future work. Finally, Section VI concludes the paper.

II. Related work

Plug-load device identification is a necessary task for power consumption measurement as described in the introduction. Administrator of power measurement equipment manually writes up the association such as which plug-load device is monitored by which point of power metering typically. For instance, power distribution unit (PDU) in a data center and smart power strip (SPS) in a building employ the manual manner. Contrary to manual, some automatic technologies are also proposed. Electric vehicle (EV) and Smart Plug have the auto identification functionality by design such as [2] and [11]. These dedicated systems have another communication channel

for the identification by modification of AC plug and power outlet.

Some researchers focused power metering itself to identify plug-load device based on time-series voltage, current and phase data. They are trying plug-load device auto identification with data analysis technology. This is a hot research topic, called as non intrusive load monitoring (NILM), includes plug-load auto identification function typically [10][12]. Other works such as [3], [4] and [9] also focus on plug-load auto identification from time-series data analysis.

Power line communication is conventionally voltage based, which modulates data to high frequency electric voltage and uses a power line system of a building as a bus network (electric voltage based power line communication, EVPLC). EVPLC is widely operated such as X10, HD-PLC[1] and G3-PLC[8]. There are an enormous number of studies[7]. EVPLC easily expands the in-building computer network because of the nature of electric voltage. Wall outlets are connected as parallel, therefore voltage signal of EVPLC propagates all outlets. However EVPLC does not aim the issue of plug-load device identification.

TWACS[6][5] is one of PLC technology and TWACS uses current flow for data communication on a power line. TWACS focuses on transmission distance of current based communication because TWACS is designed for auto power metering from the power company to their customer. Inbound communication of TWACS, from the power meter to a master device, uses current flow to transmit data in order to enable long-distance transmission around tens kilometers.

III. ELECTRIC CURRENT BASED POWER LINE COMMUNICATION

This section explains the proposal, electric current-based power line communication (ECPLC). ECPLC is a new type of communication method designed for plug-load device auto identification system. The proposal includes circuit designs of ECPLC transmitter and receiver. An electrical model of the ECPLC communication system is also introduced.

A. Plug-load device auto identification system with ECPLC

The overview of the proposed system is shown at Fig. 1. All of plug-load devices transmit an own device identifier such as an IPv6 address and Ethernet MAC address to smart power strips, a smart outlet or smart meters by electric current flow. These smart devices receive the identifier and then identify own target devices. The result of this identification may send to a center storage server, which saves power consumption data and the server keeps association correctly.

This paper uses terminologies, which are *smart meter*, *smart outlet* and *smart power strip*, for the following contents. The Smart meter indicates a power consumption metering unit for the root of power lines, which is located on the electrical panel typically. Smart outlet indicates a wall outlet with power consumption metering and smart power strip is an extension power cable with the metering function.

ECPLC is suitable for the system, because signals of ECPLC propagate to upstream of a power line by consuming electricity in ECPLC transmitter and other power outlets which
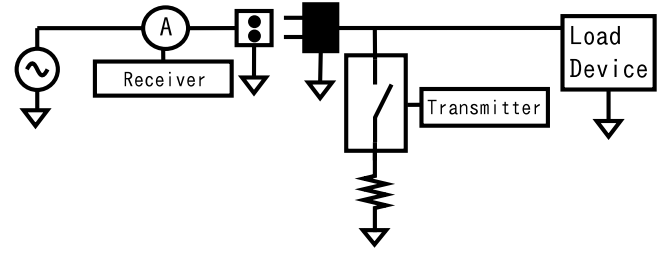

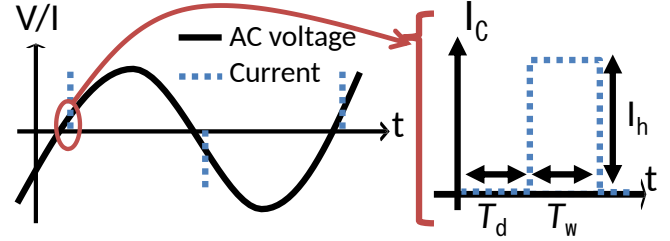Fig. 1. Plug-load device auto identification system based on electric current flow based communication

Fig. 2. ECPLC waveform: Current pulse at voltage zero crossing point

are connected as paralell do not receive signals based on physics of current flow unlike EVPLC.

B. ECPLC waveform

Fig. 2 shows a fundamental idea to represent binary value (1 or 0) on current flow and the parameters, T_d, T_w and I_h. ECPLC makes a short term current pulse at voltage zero crossing point to send "1" and no pulse at the point means "0". In another word, it is binary coded pulse width modulation on voltage zero crossing point. Using a zero crossing point makes good signal-to-noise ratio, because almost none of the plug-load devices consume electricity at the time range.

This proposed waveform has three parameters, which are T_d, T_w and I_h in Fig. 2. T_d stands for a delay before starting a pulse. T_w and I_h are the pulse width and height.

C. ECPLC Transmitter

The proposed transmission method is based on the constant current source circuit. Fig. 3 shows an important part of the proposed transmitter circuit. An AC plug is a power source and an AC input capable photocoupler is placed on the AC line in order to catch zero crossing point for a micro computing unit (MCU). A diode bridge is placed on same AC line and AC voltage is converted to full rectified wave. The output of the diode bridge connects to GND and the gate of Tr_1, an NPN transistor. An operational amplifier (op-amp), Tr_1 and a resistor compose the constant current source circuit. The MCU controls the constant current source circuit based on the output of the photocoupler.

V_{in}, V_+, V_- and V_R stand for the input voltage of the constant current source, the positive input voltage of the op-amp, the negative input voltage of the op-amp and the output voltage of the op-amp respectively as shown in Fig. 3. The op-amp makes constant current flow by V_{in}. The op-amp controls own output voltage to maintain $V_+ = V_-$. V_{in} directly connects to V_+ and V_- also directly means V_R, thus, $V_R = V_{in}$. Finally, I_h is determined as V_{in}/R_C because of $V_R = V_{in}$.
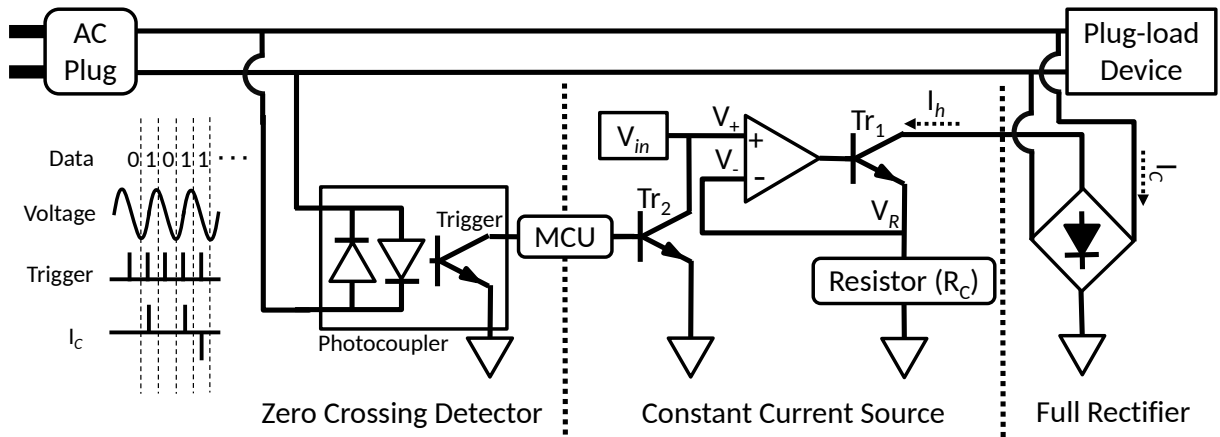
Fig. 3. ECPLC Transmitter: the transmitter makes current pulse at voltage zerocrossing timing to represent data to be transmitted.

The MCU makes $V_+ = 0$ except zero crossing timing by turning on Tr_2. Light emitting diodes (LED) of the photo-coupler are connected to the AC line. On the low voltage timing, LEDs do not emit light and the photo transistor goes to turn off. When the MCU caches the zero crossing from the photocoupler, the MCU waits T_d and turns off Tr_2 to make constant current flow as I_h in T_w period.

D. ECPLC Receiver

We propose two types of ECPLC receivers, which are with voltage (normal receiver) and without voltage (simple receiver), because of the real situation on deployment of smart outlets, smart plug strips and smart meters. Smart outlets and smart plug strips have a voltage sensing unit to calculate power consumption accurately. However, at the smart meter level, some conventional smart meters do not have voltage sensing. The smart meters assumes that power factor = 1 and simply provides apparent power (VA).

The receivers' circuit is shown at Fig. 4. The receivers measures current flow by a current transformer (CT) and catches the edges of current flow in order to detect current pulses. The conditions to accept a pulse are that height of the edge is I_h with under 30% errors and the time difference between two edges is T_w with under 10% errors. Detecting a pulse means the receiver gets 1.

The simple receiver measures current flow only as shown as Fig. 4. Therefore, to receive 0, the receiver interpolates 0 based on the time difference between "1" to "1". For instance, if the receiver receives two current pulses at t and $t + 32$ milliseconds. Two "0" are interpolated on between 1 on t and 1 on $t + 32$ milliseconds, because there are two times zero crossing on 50 Hz power systems. The normal receiver does not have this function because the receiver detects the time slot of ECPLC transmission by the voltage zero crossing detector.

E. Model of ECPLC signal transmission

Here, we introduce an electrical model of the ECPLC communication system shown at Fig. 5. R_{P1} stands for resistances on in-building power lines and R_{P2} stands for the extension power cable from the ECPLC receiver to the ECPLC transmitter. R_{INT} is an internal resistance of the transmitter.
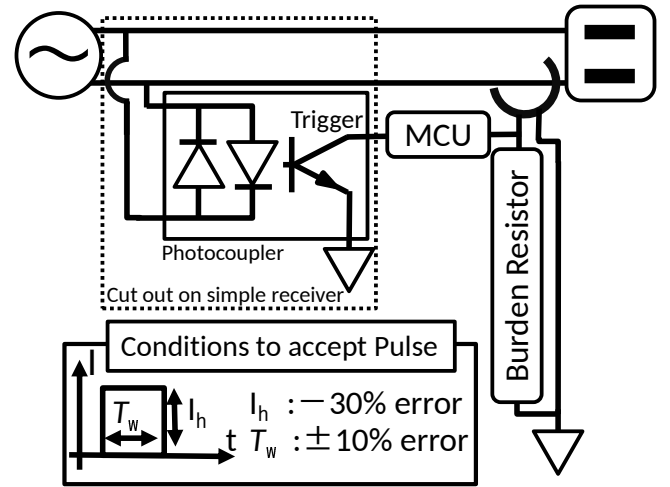

Fig. 4. ECPLC Receiver: Receiver measures current flow by the current transformer and detects transmitted pulse based on the conditions. Simple receiver does not have the zero crossing detector.

The transmitter consists of the switch, the constant current source and the internal resistance. The current source makes I_h in $T_d < t < T_d + T_w$ period. $V_{AC}(t)$ is determined as Eq. 1. The ECPLC signal transmission can be considered on this resistance only model circuit without capacitance and inductance of cables, because of frequency of ECPLC. The width of the current pulse is assumed from 100 to 500 microseconds and this corresponds 5 kHz to 1 KHz, therefore the model can ignore them.

$$V_{AC}(t) = \sqrt{2}V_{sys}\sin(2\pi f_{sys}t) \qquad (1)$$

A time-series ECPLC current flow function, $I_C(t)$, can be determined as Eq. 2. V_{sys} and f_{sys} stands for the AC power supply voltage and its frequency respectively. R_{P1} is under 1.5 Ω in 100 V power system like Japan because voltage must be between 90 to 110 V with maximum current 15 A. 10 V voltage drop with 15 A means 1.5 Ω. R_{INT} depends on the transmitter implementation. For instance, in the experimental implementation of this paper, the resistance is 0.5 Ω.

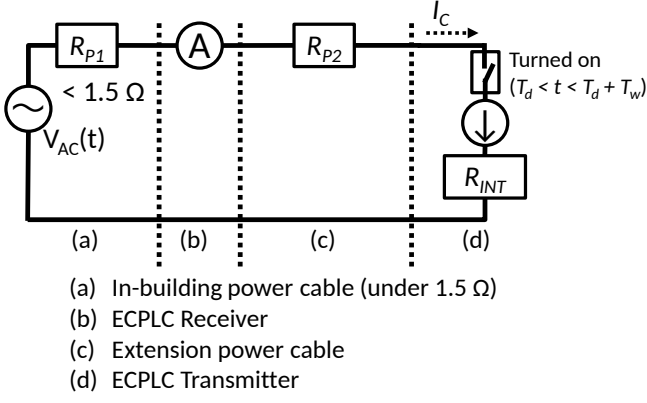(a) In-building power cable (under 1.5 Ω)
(b) ECPLC Receiver
(c) Extension power cable
(d) ECPLC Transmitter

Fig. 5. Electrical model circuit for ECPLC communication system

Fig. 6. Experiment system: the transmitter connects two receivers, normal receiver and simple receiver, via the extension power cable.

$$
I_C(t) = \begin{cases} 0 & (t < T_d) \\ 0 & (T_d + T_w < t) \\ \min\{\frac{V_{AC}(t)}{R_{INT}+R_{P1}+R_{P2}}, I_h\} & (otherwise) \end{cases} \quad (2)
$$

The maximum pulse height is capped by T_d. T_d is determined from I_h as Eq. 3, This equation is deformed from Eq. 2 with $I_C(t) = I_h$. From the equation, for instance, the case of 5.5 A for I_h requires 250 microsecond delay as T_d with $R_{P2} = 0$, $R_{INT} = 0.5$ Ω and $R_{P1} = 1.5$ Ω.

$$
T_d \geq \frac{1}{2\pi f} \arcsin(\frac{R_{INT} + R_{P1} + R_{P2}}{\sqrt{2}V_{sys}} I_h) \quad (3)
$$

T_w is considered from the receiver's analog-to-digital converter (ADC) sampling frequency, f_{ADC}, as shown in Eq. 4. For instance, if the frequency is 60 kHz, T_w is over 167 microseconds, because of the receiver design. We defined the acceptable error rate is 10% as defined in the previous section. $\pm$ 16.7 microseconds error should be occurred by 60 kHz sampling, thus T_w should be over 167 microseconds.

$$
T_w \geq \frac{1}{f_{ADC}} \times 10 \quad (4)
$$

I_h is decided by the designed power consumption to send "1" of the transmitter. The maximum power consumption, W_h, is calculated from Eq. 5. The reason of the multiplication by $2f_{sys}$ is that the time range from T_d to T_d+T_w is for a half part of a wave. From the equation, I_h can be determined by power consumption. For instance, on the case of power consumption should be under 3 W, the ADC frequency of the receiver is 60 kHz and the other parameters are same as above paragraphs, hence up to 6 A can be used.

$$
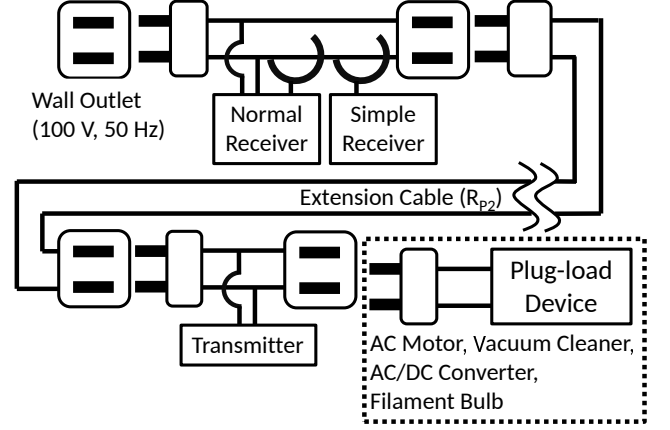W_h = \int_{T_d}^{T_d+T_w} I_C(t)V_{AC}(t) \cdot dt \times 2f_{sys} \quad (5)
$$

IV. EVALUATION

This section describes the prototype implementation of ECPLC and experimentation to evaluate characteristics of EC-PLC. We conducted two experiments. First one is to investigate the effect of the resistance of the extension cable, R_{P2}. Second one is impact of load current flow of the plug-load device itself to the communication success rate.

A. Experiment Setting

Experiment system is a one-to-one connection of the transmitter and two receivers, normal receiver and simple receiver, as shown in Fig. 6. The power cable drum between the transmitter and the receivers is the extension power cable for R_{P2}. The power source is the wall outlet of our building (50 Hz and 100 V).

Hardware configurations of the experimentation are summarized in TABLE. I. MCUs (model: ATMEL ATmega328P) is used for the receivers. The MCU takes a current value from the ADC and demodulates binary data. The receivers use a CT (model: U_RD CTL-10-CLS) with 1 kΩ burden resistor as the current sensor. The normal receiver uses a photocoupler (model: Fairchild Semiconductor FOD814A300W) as the zero crossing detector. The transmitter makes constant current by the op-amp (model: HTC LM358N) and two transistors (model: TOSHIBA 2SC5200, 2SC3421) as a Darlington pair. The output of the op-amp connects to the Darlington circuit to make current pulse. The MCU (same as receivers) connects to the op-amp and works as the binary pulse width modulator.

To evaluate the ECPLC experiment system, here, we determine example parameters as $T_d = 250$ microseconds, $I_h = 5.5$ A and $T_w = 350$ microseconds. To calculate a success rate, the transmitter sends pseudo-random 32bit sequence 200 times, 800 bytes. Success rate is defined as if the receiver demodulates the 32bit chunk correctly that it means success, but if there is any bit errors that it is fail. In addition, throughput of the implementation is 100 bps because of the power system frequency 50 Hz.

B. Pulse width decreasing on extension power cables

Fig. 7(a) shows shapes of current pulse on the three cables which are 100 m (0.98 Ω), 60 m (0.64 Ω) and 4 m (0.10 Ω)

| Simple Receiver	
MCU	ATMEL ATmega328P, 16MHz, 2KB SRAM
ADC	MCU internal, 60 kHz
Current sensing	CT, U_RD CTL-10-CLS
Burden resistor	1 kΩ
Normal Receiver	
MCU	ATMEL ATmega328P, 16MHz, 2KB SRAM
ADC	MCU internal, 60 kHz
Current sensing	CT, U_RD CTL-10-CLS
Burden resistor	1 kΩ
Voltage sensing	Fairchild Semiconductor FOD814A300W
Transmitter	
MCU	ATMEL ATmega328P, 16MHz, 2KB SRAM
Voltage sensing	Fairchild Semiconductor FOD814A300W
Constant current source	HTC LM358N, TOSHIBA 2SC5200, 2SC3421
R_C	0.39 Ω
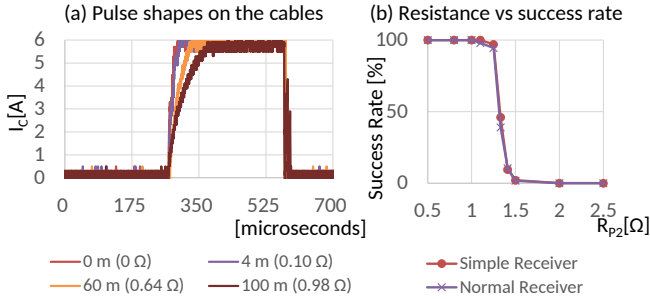
Fig. 7.   (a) Shapes of current pulse on different cables. (b) Communication success rate versus the resistance of extension cable.

respectively. We changed R_{P2} on Fig. 5 by the three cables. The series named as 0 m means that the transmitter connects to the receiver without an extension cable. The width of the current pulse is decreased on longer power cable because of R_{P2}. 60 m and 100 m data indicate the error of pulse width increases on the longer cable (higher resistance).

This result follows proposed ECPLC communication model in Section III, because the pulse width decreasing is caused only by the resistance of the cable. *i.e.,* Inductance and capacitance are negligible.

We inserted a variable resistance between the extension cable and changed R_{P2} intentionally so as to measure success rate versus resistance as shown at Fig. 7(b). There is no major difference between the two receivers. The result shows that communication success rate has rapidly decreased from around 1.1 Ω. This value corresponds to the cable length between 100 m to 200 m.

C. Communication with various plug-load devices

Fig. 8 shows current waveforms from the ECPLC transmitter with four different plug-load devices which are AC motor, filament bulb, vacuum cleaner and AC/DC switching converter without the extension cable, R_{P2}. Purple line shows the voltage on the AC power line and blue lines show current flows, I_C. The current pulses of ECPLC are modulated at around voltage zero crossing timing.

The four devices are chosen to investigate ECPLC characteristics with various plug-load devices power consumption pattern. In order to examine characteristics of low power factor device, a 70 W AC motor (Motor) is selected. The AC motor has mechanical impedance and the magnetic thing inside it

and the power factor is around 60% to 80%. To evaluate with the nonlinear, conventional consumer electronics device, an AC/DC switching converter (ACDC Con.) with a resistor is tested. Quite a few numbers of consumer electronics device require DC power and these devices use the converter. For evaluation with huge power consuming device, a filament bulb (Bulb) and a vacuum cleaner (Vacuum) are selected.

We evaluate success rates versus pulse width and height with the four plug-load devices and no device as shown as Fig. 9. The NL series means that there is no plug-load device, *i.e.* direct connection of the transmitter and the receivers. Both receivers get transmitted data correctly even the low power factor device or the AC/DC switching converter, with the default parameters, $T_d = 250$ microseconds, $T_w = 350$ microseconds and $I_h = 5.5$ A. Moreover, with lower pulse height around 2 A, the normal receiver obtains data correctly. However the simple receiver does not collect enough data with the vacuum cleaner or with lower pulse height. The receiving process in the receiver is compromised because of vibrations of load current of the devices. For instance, the vibration of the vacuum cleaner is quite huge around $\pm$ 4 A. The process tries to catch 4.62 A (70% of 5.5 A) up/down edge of the pulse. The threshold value is nearly closed to the vibration, therefore the receiving process does fail. With lower pulse height, the process is also damaged because of the same reason. The normal receiver only works on zero crossing points and, thus, can avoid the vibrations.

V.   DISCUSSION AND FUTURE WORK

Many-to-one connection is a future work of this research. In this paper, we tested the ECPLC system on the one-to-one connection between the transmitter and the receiver in order to evaluate characteristics. On the deployment of the power metering device, there are some granularity levels, which are smart power strips, smart outlets and smart meters. All plug-load devices monitored by an individual smart power strip are the novel scenario and the scenario is just one-to-one connections. However, in the practical environment, smart power strips and smart outlets are extended by conventional power strips and some plug-load devices connect to one receiver and the connection must be many-to-one. ECPLC needs a method of collision management to treat the many-to-one connection.

Deep analysis and design of the detailed electric model of communication is surely important tasks. This paper introduces new communication mechanisms and provides some results based on the prototype to prove our concept. To discuss ECPLC mechanism more deeply, detailed electric model and new definitions of communication perspective are required. For example, to draw a graph of BER (Bit Error Rate) versus noise level requires a definition of noise of ECPLC.

ECPLC receiver may be implemented on conventional smart metering devices from the results of the experimentation because the pulse width is around 100 microseconds and the width is enough to measure by conventional ADC sampling rate. Considerations of developing the ECPLC communication system with the conventional deployed smart metering system is also a fancy future work.
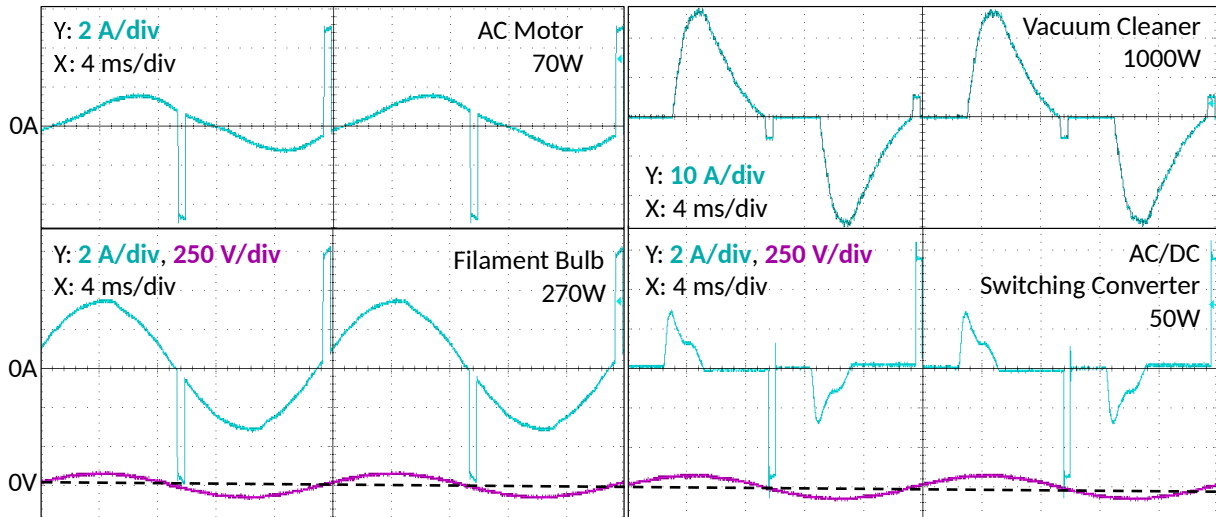
Fig. 8. ECPLC current pulse on plug-load devices current flows; Four images are screenshots from an oscilloscope (model: Tektronix MDO3014) and the series is centered by a downside edge of a pulse. The y-axis of the top-right one is different with others.
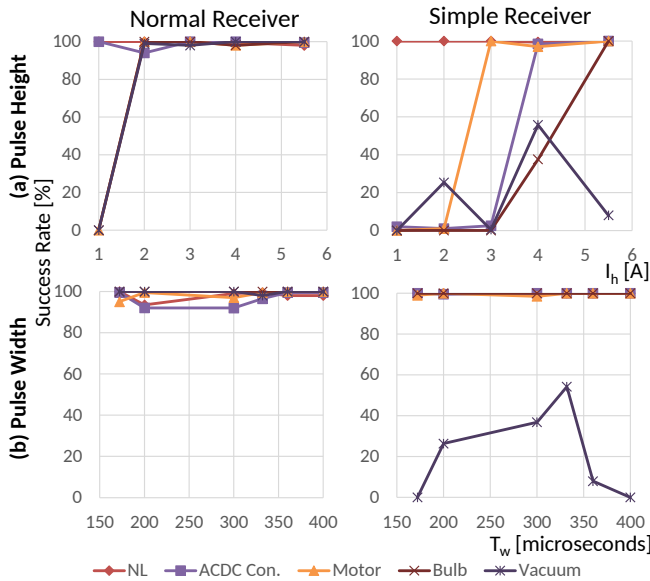

Fig. 9. Success rate versus pulse width and height: (a) pulse height, I_h, and T_w is fixed to 350 microseconds; (b) pulse width, T_w, and $I_h = 5.5$ A.

VI. CONCLUSION

This paper presents electric current based power line communication (ECPLC). Feature of ECPLC is propagation range – transmitted signals limited on the connected smart power meters against conventional voltage based power line communication (EVPLC). The experimentation with working prototype shows ECPLC works well and characteristics are suitable for typical building environments. Throughput of ECPLC is achieved at 100 bps, which is enough for the target application, plug-load device auto identification system. The result of the experimentation shows that plug-load device auto identification system with ECPLC is feasible.

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