RTL Design of FA-WLAN System and its Verification

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Abstract: In this work, we propose an industrial Wireless Local Area Network(iWLAN) system for industrial robots(iRBs) control in factory automation(FA) environments. For fast and deterministic communication, we apply a synchronous multi-user(MU) round-robin transmission protocol. To reduce the overhead caused by the conventional multi-user downlink transmission technique, we then propose a low overhead Packet Division Multiple Access (PDMA) transmission technique. The analysis and simulation results show that our proposals provide 100% better throughput than the conventional system(iPCF). Furthermore, the architecture of iWLAN system is proposed and designed to successfully implement the proposed protocol. The RTL verification result of the proposed system is also shown.

1. Introduction

In recent years, wireless technology has emerged as a promising alternative for industrial communication because it can provide the flexibility needed for mobile robot settings. The wireless technology also has an advantage for the FA systems that it reduces the cable connectivity and maintenance costs.There are several solutions for FA wireless communication. Bluetooth, which is based on IEEE 802.15.1 protocol, is widely used for short-range transmission applications For greater transmission range, Zigbee, which is based on IEEE 802.15.4 protocol, is proposed Although Zigbee provides long-range transmission, its slow data rate makes it only suitable for wireless sensor network applications [1]. In order to improve the data rate and reliability of Zigbee, the industrial communication standard WirelessHART, which is also based on the IEEE 802.15.4, has been released [2]. However, the disadvantage of WirelessHART is the poor compatibility with IEEE 802.11 WLAN devices [3].

The IEEE 802.11 WLAN technology provides higher data rate, greater range than the WirelessHART. In addition, it is easy to coexist with other WLAN office devices. For those reasons, the industrial communication systems based on IEEE 802.11 WLAN technologies have been gradually developed in the FA field. In [4], the retransmission algorithm is introduced to optimize the retransmission number to increase the throughput of the IEEE 802.11g. In [5], the enhanced distributed channel access (EDCA) is investigated to provide low latency for the IEEE 802.11e. However, since both of them operate under the Distributed Coordination Function (DCF) access technique, the sequence of transmissions is non-deterministic. The determinism is an important factor for safe industrial communication systems. To deal with this problem, PROFINET has offered an industrial WLAN

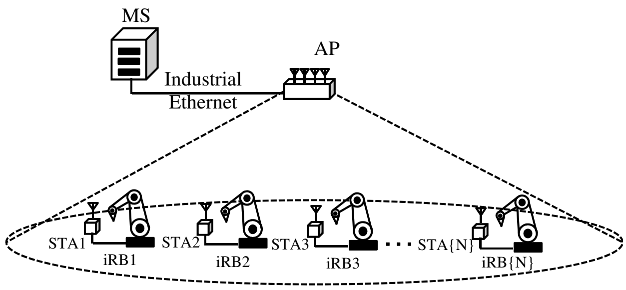

Figure 1. FA-WLAN System Model

system using iPCF protocol [6]. In this protocol, the Master (MS) controls the sequence of transmissions to iRBs by using a polling mechanism. However, the throughput of this protocol is slow because it supports only single user (SU) transmissions [7]. In addition the number of iRBs in FA system is large. The duration for one round of all iRBs communications can get so big, that it causes real-time control failure.

In order to mitigate the aforementioned problems of the current FA systems, we propose a novel MU iWLAN system capable that is both fast and safe. The analysis and simulation results show that our proposals provide 100% better throughput than the conventional iPCF [8]. The contributions of this paper include: Section 2 shows the FA wireless communication system model with the conventional and proposed transmission protocols. In Section 3, to reduce the critical overhead caused by the conventional MU - multiple inputs and multiple outputs (MIMO) downlink (DL) SDMA transmission technique, we propose a low overhead PDMA transmission technique. In Section 4, The architecture of iWLAN system is proposed and designed to successfully implement the proposed protocol. The RTL verification result of the proposed system is also shown. Finally, Section 5 outlines our conclusions of this paper.

2. FA-WLAN System

Fig. 1 shows the system model of FA-WLAN System. Access Point(AP) is installed to MS and Station(STA) is installed to iRB. AP communicates to STA in wireless and transmits the orders of MS to iRB.

2.1 Conventional iPCF System

The iPCF protocol supports the deterministic feature. This protocol is developed based on the PCF protocol from IEEE 802.11 standard. The iPCF provides Contention Free Period (CFP) for frame transfers. The sequence transmissions of

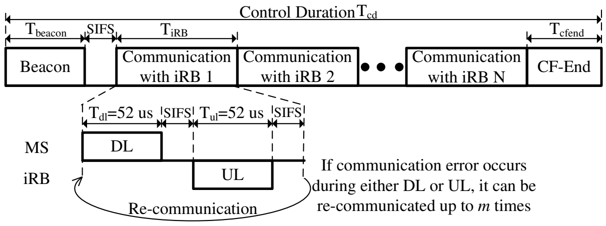

Figure 2. Conventional iPCF protocol

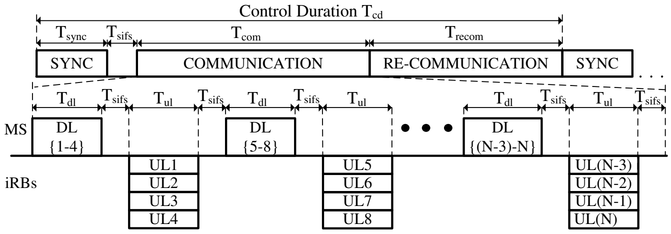

Figure 3. Proposed iWLAN Protocol

iRBs is determined by a contention free polling mechanism. Fig. 2 shows the protocol diagram of PCF. In this protocol, MS uses a round-robin polling with SU to communicate with *N* iRBs. During the communication with each iRB, if DL or uplink (UL) transmission errors are detected, MS will retransmit DL frame after Short Interframe Space (SIFS) or PCF Interframe Space (PIFS) intervals, respectively. MS announces the end of CFP by broadcasting the CF-End frame. Because the iPCF protocol supports only Time Division Multiple Access (TDMA) technique with SU transmissions for both DL and UL, the throughput of the iPCF system is slow.

2.2 Proposed iWLAN System

In order to mitigate the limitation of SU transmissions in the iPCF protocol, we propose an advanced synchronous MU round-robin iWLAN transmission protocol. Beside the deterministic feature, our protocol also supports MU access for both downlink(DL) and uplink(UL) transmissions. Fig. 3 shows the protocol diagram of our proposed iWLAN. The sequence operations of protocol includes 3 stages:

- Stage 1(SYNC): MS starts a new control duration (T_{cd}) by broadcasting a synchronization (SYNC) frame to all iRBs on the bandwidth of 80 MHz. This SYNC frame carries the information of the Precision Time Protocol (PTP). The duration of SYNC frame transmission is denoted by T_{sync}.
- Stage 2(COMMUNICATION): MS communicates with all *N* iRBs. This communication duration is denoted by T_{com}. This interval includes the following operations:
  - DL transmission: After the wait of SIFS duration (T_{sifs}), MS transmits the MU-DL frame to iRBs on the bandwidth of 80 MHz. We support MU-DL frame of up to 4 users using Packet Division Multiple Access(PDMA) technique. The values of *u* can be 1, 2, 3 or 4. The duration of DL transmission is denoted by T_{dl}.
  - UL transmission: If iRB successfully receives its data from DL frame, it will respond to MS after T_{sifs} by sending UL frame using bandwidth of 20 MHz. Up to 4 iRBs are supported to send their UL frames simultaneously using Frequency Division Multiple Access (FDMA) technique. The duration of UL transmission is denoted by T_{ul}.
  - The DL and UL transmissions are performed until MS finishes sending data to all of *N* iRBs. An iRB error occurs if the iRB fails to either receive the DL packet from MS or transmit the UL packet to MS.
- Stage 3(RE-COMMUNICATION): If there are any iRB errors during stage 2, the MS will re-communicate with them again. This re-communication duration is denoted by T_{recom}. The operations during this stage are the same with stage 2. Stage 3 is repeated until MS successfully communicates with all *N* iRBs or the T_{cd} elapses. When the T_{cd} elapses and there is not any iRB error in this stage, a new T_{cd} is performed.

3. MU DL Transmission Techniques

In the proposed iWLAN transmission protocol in section 2.2 we employ the MU transmission technique for DL access to enhance the throughput of the FA communication system. The FDMA and SDMA are the conventional transmission techniques which support the MU DL access. In the proposed iWLAN protocol, because the iRBs receive SYNC frames on channel bandwidth of 80 MHz, they cannot receive the DL frames on different channel bandwidth by using the conventional FDMA technique. In this section, we firstly present the conventional MU-MIMO DL SDMA technique, then we show our proposed MU-PDMA DL technique.

3.1 Conventional MU-MIMO SDMA DL Technique

For MU DL transmissions, the MU-MIMO SDMA is an emerging technique in the 802.11ac WLAN systems [9] because access point (AP) can simultaneously transmit independent streams to MU on the same channel by applying crosstalk interference (CTI) minimizing precoding vectors [10]. The MU-MIMO SDMA DL technique is shown in Fig. 4. At AP, the MAC Service Data Units (MSDUs) of four users, $MSDU_{(1-4)}$, are precoded into four transmission frames $SDMA_{(1-4)}$. Then, these four frames are transmitted through four different antenna streams on the same channel of 80 MHz. At each user, its MSDU is decoded from the received interference $SDMA_{\{1,2,3,4\}}$. In order to help each user to decode its data, the AP requires the channel state information at transmitter (CSIT) for the pre-coding process. To get the CSIT, it takes a critical overhead duration to perform the sounding procedure before the data transmissions (MU-MIMO transmissions), as shown in Fig. 5. The sounding period includes the sounding procedure and the MU-MIMO transmissions. The sounding procedure exchanges the messages of the Null Data Packet Announcement (NDPA), Null Data Packet (NDP), Compressed Beamform-

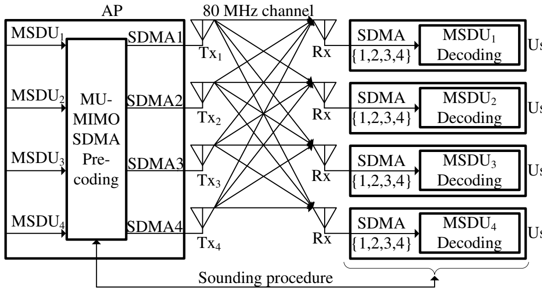

Figure 4. MU-MIMO SDMA DL technique

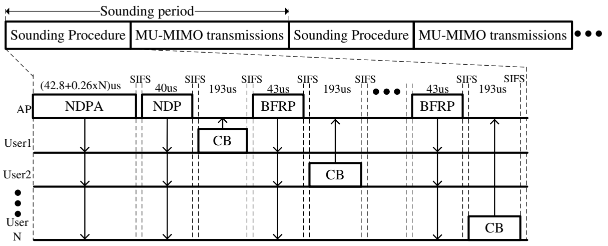

Figure 5. Sounding procedure in MU-MIMO SDMA DL technique

ing (CB) and Beamforming Report Poll (BFRP) between AP and users. The CB duration (193 μsec) and BFRP duration (43 μsec) make the sounding overhead of each user approximate 236 μsec [9]. The MU-MIMO transmissions exchange the control data between AP and users.

In WLAN systems with the MU-MIMO SDMA DL technique, the data transmission frames are long and the sounding periods are also long, approximately $N \times 20$ miliseconds [11], then the overhead of sounding procedure is only a small proportion of the sounding period. Therefore, this overhead is not critical for WLAN systems. Meanwhile, in the FA communication system, the data transmission frames are short and the target control duration, T_{cd}, is also short, approximately $N \times 100$ microseconds, then the overhead of sounding procedure becomes extremely critical. To mitigate the critical overhead for MU DL transmissions, we propose a low overhead MU-PDMA DL technique.

3.2 Proposed MU-PDMA DL Technique

In order to support the MU DL access with low overhead for FA communication systems, the MU-PDMA DL transmission technique is proposed, as shown in Fig. 6. At access point (AP), the MSDU data of four users, $MSDU_{(1-4)}$, are merged into one transmission frame, called MU-PDMA. Then, this MU-PDMA frame is transmitted to all users through one antenna stream on the same channel of 80 MHz. This MU-PDMA frame can also be transmitted to all users through four antenna streams to get the diversity gain. At each user, its MSDU is extracted from the received MU-PDMA frame. The format of MU-PDMA is shown in Fig. 7. To make the our FA system compatible with the WLAN system, the format of MU-PDMA frame adheres to the IEEE 802.11 standard, that is comprised of the PHY header, MAC header,

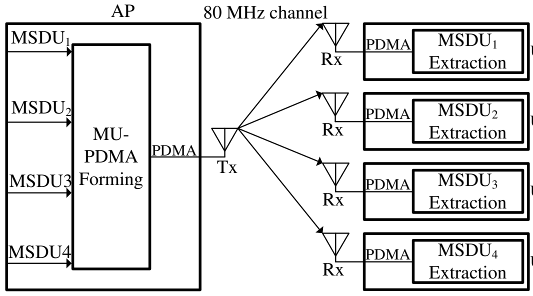

Figure 6. Proposed MU-PDMA DL technique

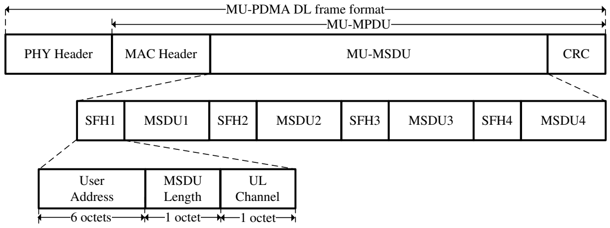

Figure 7. Proposed MU-PDMA DL frame format

MU-MSDU and cyclic redundancy check (CRC) data. The MU-MAC Protocol Data Unit (MU-MPDU), which is comprised of the MAC header, MU-MSDU and CRC data, is constructed on MAC layer. Then, the MU-PDMA frame, which is comprised of the PHY header and MU-MPDU data, is constructed on PHY layer. To delimit the data of each user in the MU-MSDU, a Sub-Frame Header (SFH) is embedded between each MSDU. The SFH includes: (1) User Address field (6 octets) that indicates the destination address of its following MSDU, (2) MSDU Length field (1 octets) that indicates the length of that MSDU, (3) UL Channel field (1 octets) that defines the channel allocated for UL transmission. At receiver side, the user gets its MSDU based on the User Address and MSDU length fields, then it performs the UL transmission on the channel indicated by the UL Channel field. The UL frame of each user is transmitted on the channel of 20 MHz.

Instead of using the critical overhead sounding procedure, the MU-PDMA DL technique uses only the small overhead SFHs (8 octets) to decode the data, therefore in FA systems, this technique provides higher throughput than the MU-MIMO DL technique.

4. RTL Design and Its Verification

The iWLAN system is designed by RTL to successfully implement the proposed protocol. In order to verify to achieve the proposed protocol, we assume various cases and need to verify in RTL. For example, the cases are classified as either no-error scenario or error scenario.

Fig. 8 shows the verification result of RTL system. It shows that MS transmits the frames to iRB1-8 in the UL bit-error scenario. The UL bit-error of iRB1 occurs. We verify the transmission and reception of frames in the aforementioned 3 stages.

- Stage 1(SYNC): MS starts a new control duration by broadcasting a SYNC frame to iRB1-8. Therefore,

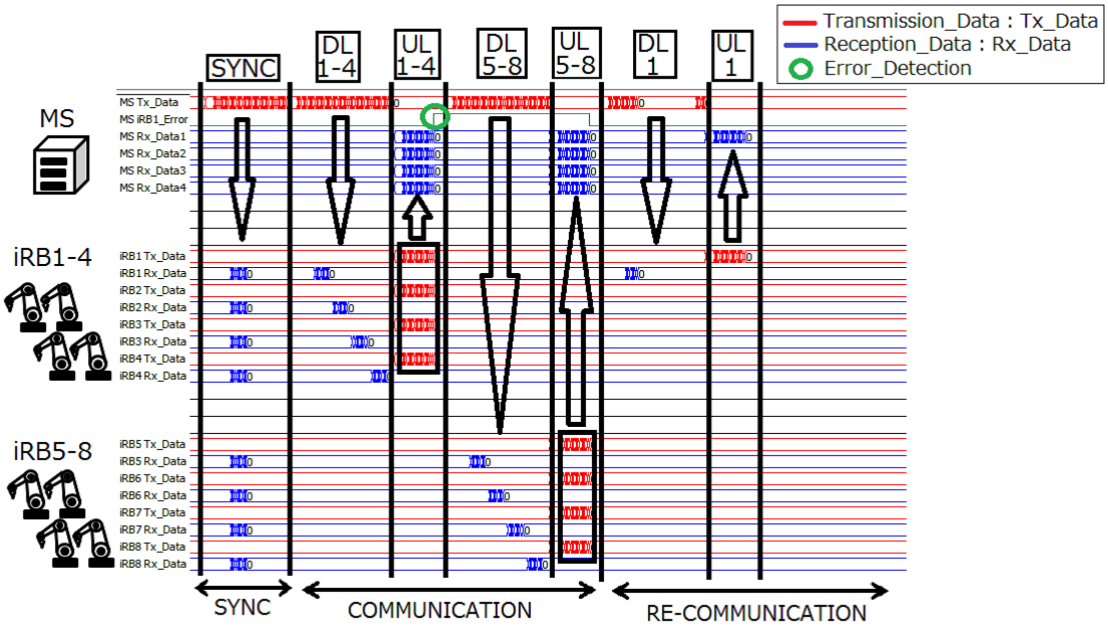

Figure 8. Communication of MS and iRB1-8 in iRB1 UL bit-error

iRB1-8 receive the same data.

- Stage 2(COMMUNICATION): MS communicates with iRB1-8. This interval includes the following operations:
  - DL transmission: After the wait of SIFS duration, MS transmits the MU-DL frame to iRB1-4 using PDMA technique. Therefore, iRB1-4 receive its data. The same is true of iRB5-8.
  - UL transmission: If iRB1-4 successfully receives its data from DL frame, they respond to MS using FDMA technique after SIFS duration. The same is true of iRB5-8. In this case, the UL bit-error of iRB1 occurs.
- Stage 3(RE-COMMUNICATION): MS re-communicate with iRB1 again because there is an iRB1 error during stage 2.

5. Conclusion

A very high throughput FA wireless communication system for robot controls has been presented in this paper. We have proposed a synchronous MU round-robin iWLAN transmission protocol. This protocol is applicable for FA communications because it supports the deterministic feature. Our protocol achieves 100% higher performance than the conventional iPCF protocol because it can support the MU transmissions for both UL and DL. We have also proposed the low overhead PDMA transmission technique for the MU-DL access. Finally, the iWLAN system has been also designed and verified in RTL.

References

[1] J.S Lee, Y.W Su and C.C Shen : A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi ; *Annual Conference of the IEEE on Industrial Electronics Society (IECON)*, pp. 46–51 (2007)

[2] HART Communication Foundation : *HART Field Communication Protocol Specification, Revision 7.0* (2007)

[3] S. Petersen and S. Carlsen : Performance evaluation of WirelessHART for factory automation ; *IEEE Conference on Emerging Technologies & Factory Automation (ETFA)*, pp. 1–9 (2009)

[4] I. Dominguez-Jaimes, L. Wisniewski, H. Trsek and J. Jasperneite : Link-layer retransmissions in IEEE 802.11g based industrial networks ; *IEEE International Workshop on Factory Communication Systems (WFCS)*, pp. 83–86 (2010)

[5] G. Cena, L. Seno, A. Valenzano, C. Zunino : On the Performance of IEEE 802.11e Wireless Infrastructures for Soft-Real-Time Industrial Applications ; *IEEE Transactions on Industrial Informatics*, Vol. 6, No. 3, pp. 425–437 (2010)

[6] G.Santandrea : A PROFINET IO application implemented on Wireless LAN ; *IEEE International Workshop on Factory Communication Systems (WFCS)* (2006)

[7] I. A. Candian : PROFIsafe and PROFINET via IWLAN ; *Siemens, Automation & Drives PICC Meeting* (2008)

[8] Duc Khai Lam, "A Fast Industrial WLAN Protocol and its MAC Implementation for Factory Communication Systems," IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2015), Sept. 2015, pp.1-6.

[9] IEEE : *IEEE Std 802.11ac/D7.0, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications* (2013)

[10] E. H. Ong, J. Kneckt, O. Alanen, Z. Chang, T. Houvinen, T. Nihtila: IEEE 802.11ac: Enhancements for very high throughput WLANs; *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 849–853 (2011)

[11] G. Redieteab, L. Cariou, P.Christin: PHY + MAC Channel Sounding Interval Analysis for IEEE 802.11ac MU-MIMO; *IEEE International Symposium on Wireless Communication Systems (ISWCS)*, pp. 1054–1058 (2012)