High-efficient Converged Digital Radio over Fibre (DRoF) Transmission and Processing for Indoor Both Cellular and IoT Services

Wen Li
School of Electronic and information Engineering
Beihang University
Beijing, China
liwen5658@buaa.edu.cn

Aixin Chen
School of Electronic and information Engineering
Beihang University
Beijing, China
axchen@buaa.edu.cn

Tongyun Li
Centre for Photonic Systems, Electrical Division, Engineering Department
University of Cambridge
London, UK
tl299@cam.ac.uk

Xuefeng Wang
Beijing Institute of Aerospace Control Devices
Beijing, China
xuefeng_wang@sina.cn

Richard Penty
Centre for Photonic Systems, Electrical Division, Engineering Department
University of Cambridge
London, UK
rvp11@cam.ac.uk

Yidong Yao
Beijing Institute of Aerospace Control Devices
Beijing, China
lolipop1923@163.com

***Abstract*—Digital Radio over fibre (DRoF) transmission has long been considered as a promising solution for providing multiple wireless services over a single optical-wireless infrastructure for indoor and last-mile wireless coverage. However, with the increasing number of services and fast growing requirement of Internet of things (IoT), the existing technologies are not able to meet the demand of network convergence due to high capital expenditure (CAPEX) and operating expenditure (OPEX) in managing the vast amount of digitised data. In this paper, we demonstrate a compact multi-service hybrid fibre radio scheme for both downlink and uplink where a novel digital signal processing method and a novel fronthaul protocol are implemented with high bandwidth efficiency. The system uses pluggable modular RF frontend and digital cards so as to support the increasing services dynamically. Both RFID based IoT services and several cellular services from mobile network operators (MNOs) are converged onto a single <6Gbps optical link with high spectral efficiency, modulation accuracy and RF performance. The system is experimentally demonstrated and shows low EVM for all cellular services provided from China Unicom and high detection rate and localisation accuracy for the RFID service carried over 20km optical fibre link.**

Keywords*—*Hybrid fibre radio system, Digital radio over fibre (DRoF), Multi-service, Cellular, Internet of things (IoT)

I. INTRODUCTION

Poor indoor wireless coverage has been recognised as one of the biggest obstacles for delivering next-generation cellular and internet of things (IoT) services. To address this issue, digital radio over fibre based distributed antenna system (DRoF-DAS) has been suggested as a promising solution for extending the coverage and bringing capacity to indoor users [1].

Traditional solutions for mobile communication indoor signal coverage can be divided into three kinds: small cell [2], leaky coaxial cable [3] and distributed antenna system (DAS). The first solution works in a single-service and single-operator environment and parallel systems must be established to support multiple wireless standards. The second solution can't meet the requirement of the future mobile communication due to its high cost and low efficiency. For large buildings, with the increasing number of services, the two solutions will increase the cost per square meter. DAS is a network of multiple antennas distributed in a building dedicated to providing wireless indoor coverage. In comparison, DAS allows multiple radio frequency sources to focus and deploy on a single optical network. As a result, the cost per square meter will not be influenced by the increasing number of services. Analogue DAS is the most frequently used DAS type as its fibre can support a frequency range as wide as 20GHz. As a result, most wireless services below 5GHz can achieve transparent transmission and analogue signals are redistributed on the whole link. However, analogue transmission has many disadvantages, including high loss, nonlinearity, and difficulty in integrating current digital network, such as Ethernet. More and more DAS suppliers are providing digital DAS (DDAS) solutions to solve these problems [4]. DDAS systems are developing towards software defined radio (SDR) and centralised radio access network (C-RAN) [5-7].

IoT, with smart city, smart grid and smart home as representation, is a key area of our nation in the future [8]. If a single network is set up to support a certain service, it will bring high capital expenditure and operating expenditure for operators and wireless network users. With the developing trend of television, telephone and computer network merging and multi-network integration, the realisation of all communication services in a single system is in urgent need.

The increasing number of services in the new generation broadband wireless mobile communication network results in a rapid growth of data throughout. 1000 fold increase in signal capacity is expected for 5G [9-10]. However, current indoor wireless solutions are not sufficient to support this extraordinary rise of capacity and number of services. The current common public radio interface (CPRI) protocol [11] in parallel transmission cannot meet the demand due to its low bandwidth utilization efficiency and incompatible between different service standards. A novel low bit rate digital processing algorithm is demonstrated [12]. In this paper, we extend the use of this algorithm and demonstrate a high-efficient DDAS with a flexible and user-definable transmission protocol carrying both cellular and IoT services for indoor wireless coverage. This broadband DDAS system can support all wireless communications from 700MHz to 6400MHz, meeting the requirement of the long term development of 5G and IoT. We believe this is the first demonstration of this kind and shows significant improvement in network convergence and infrastructure sharing.

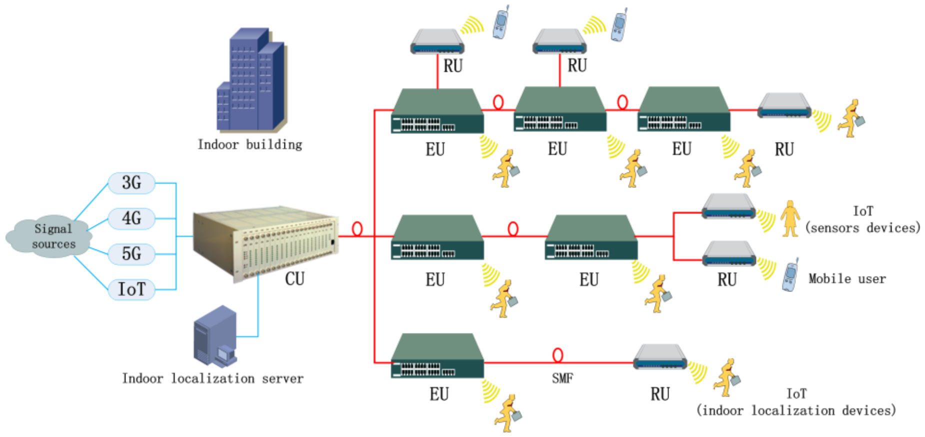

Fig. 1. The architecture of the multi-service wireless signal transportation system

II. PROPOSED MULTI-SERVICE DDAS SYSTEM BASED ON DROF TECHNIQUE

A. System Architecture

As Fig. 1 shows, the novel multi-service wireless signal transportation system based on DRoF technique with high bandwidth efficiency adopts a three-layer DDAS structure, which can meet the demand of indoor mobile signal and IoT signal coverage. It is composed of central unit (CU), extent unit (EU) and remote unit (RU). The CU couples downlink signals from the signal source into the system. The signals are compressed and packetised after being converted into digital signals. Then they are transported to EU or RU by single-mode-fibre (SMF) after the electro-optical conversion. At the same time, optical signals are depacketised and decompressed after the opto-electrical conversion, they are converted into uplink RF signals and transported to the signal source. The CU is an enabler to flexibly support diverse communication requirements for the next generation wireless communications. Multiple types of service board can be plugged into the CU as needed with each service board having ADC/DAC and corresponding RF circuit, so multi-service signal sources such as IoT can be accessed into the CU dynamically. The EU transmits the digital signals sent by the CU to different RUs. At the same time, signals sent by different RUs are converged and then transported to the CU. The EU supports a recurrent network to enlarge the networking and carrying capacity of the system. The EU supports the long-distance power supply to the RU. The EU supports the long-distance monitoring and management of its own RU. The RU transmits the digital signals sent by the CU or the EU into RF signals. In this way, the indoor coverage of mobile communication signals is realized. At the same time, the RU converts the received uplink signals into digital signals and transmits them to the EU or the AU. The AU, EU and RU support the access of IoT service and provide a transmission channel for IoT data.

Low frequency 125K RFID activator and 2.4G reader are integrated in the EU and the RU. 125K RFID activator is connected to four localisation antennas through shielded wire with two cores and actively sends low frequency pulse signal through antenna (the antenna number is included in the carrier data). When the localisation tag receives activation signal from an activator, its low frequency chip will analyse the antenna number in real time and detect the received signal strength indication (RSSI) value of the low frequency signal. Then the 2.4G wireless RF chip in the tag is opened to send strong signals containing the tag ID, the antenna number and the received RSSI value. The 2.4G reader in the EU or RU receives the signal sent by the tag in 2.4G frequency band, then analyses the localisation data including the tag ID, the antenna number and the RSSI value. The localisation data, together with other business data, is packetized and sent to the AU. Application server connected to the AU will process the reported localisation data, periodically calculate the population of each area and check if they enter key areas illegally.

The system provides data transmission with high-quality service and high efficiency. It not only lowers the cost with great upgradability, but also supports the integration of multiple wireless signal service into a single basic network, such as Ethernet. Thus, it provides the signal coverage for new-generation broadband mobile communication networks. Besides, it provides support for the services of mobile Internet and IoTs. Its advantages include low lost, easy operation and maintenance, low energy consumption and software upgradability.

B. Novel digital signal processing

In [13-14], a DRoF system with the use of bandpass sampling technology is described. However, this method brings about high data transmission rate and a high-cost optical network needs to be built in practice. As RF signal is considered as narrow-band signal from the perspective of optical communication, it is possible to use data compression algorithm to lower the transmission rate needed. Take downlink as an example, in the DDAS system, RF service signals from application point (AP) or base station (BS) are detected and injected into the RF front end in the CU. As the

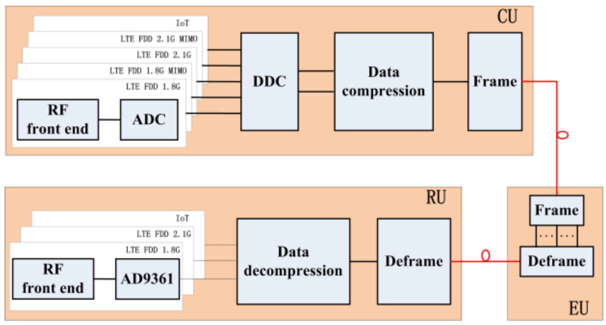

Fig. 2. Flow chart of the novel digital signal processing

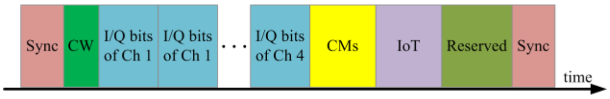

Fig. 4. The architecture of user-defined protocol

frequency ranges of the signals are very wide, signals in different ranges are mixed and down converted to intermediate frequency (IF) to meet the bandwidth requirement of ADC [15-16]. After the conversion to digital signals by ADC, further digital signal processing is carried out, including digital down conversion (DDC) and data compression. Then the compressed data is packetised and optical conversion is carried out. Low bit rate data is transmitted through optical fibre. The EU receives the fibre data from the AU and transmits it to the RU. The RU first depacketises the received signals and then reconstructs them. The reconstruction process includes interpolation and digital-to-analogue conversion. In the end, the zero IF chip up-converts the digital signal to RF signal. The uplink process is the same where signals are transmitted to AP or BS from the RU.

The novel digital signal processing method not only lowers the network requirement of the system in Fig. 1, but also makes the use of low-cost transmission media viable, such as twisted pair and long-distance fibre. The method makes the use of distributed system in both LAN and WAN possible and allows the system to share transmission media with other services.

C. User-defined Protocal

Up to now, no DDAS system can support mobile communication service and IoT service at the same time. By realizing the IP transmission of DDAS, the novel DDAS system integrates mobile communication data and IoT data into a single transmission protocol, allowing DDAS system to support IoT service, such as RFID with the use of current IP network.

Fig. 3 shows the system architecture of the whole user-defined protocol. Business data from different channels is transmitted in the format of IQ data and IQ data from different channels are transmitted in a single transmission link by the method of time division multiple access (TDMA). At the same time, the monitoring and control messages (CMs) of different channels as well as IQ data are transmitted together by the method of TDMA. IoT data with different throughput rates are also inserted into the frame structure and transmitted. In order to recover the data in the remote end, synchronisation word (Sync) and control word (CW) need to be added in the protocol. At last, extra bits can be reserved for the transmission of future 5G service data. The protocol has many advantages, such as flexibility and high bandwidth efficiency, allowing the system to customize extended services according to its own needs.

III. Experimental Setup

According to the distribution of different frequency bands of China Unicom, the project is designed to support 3G and 4G services of China Unicom as well as indoor localisation service of IoT. The frequency bands of China Unicom services and IoT services are shown in Table 1. The experimental setup is depicted in Fig. 4. Take the uplink test as an example, we used the Rhode and Schwarz (R&S)

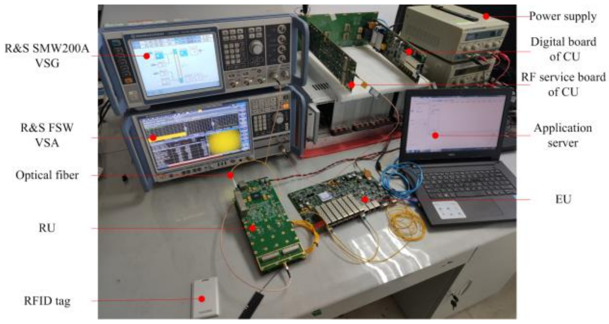

Fig. 3. Experimental setup

SMW200A vector signal generator (VSG) to generate our 16-QAM LTE uplink signal for testing the services of China Unicom. In the RU, a single AD9361 can receive the RF signals of 2 MIMO services in the same frequency band and send digitalized signals into FPGA. In the FPGA, the resampling rate of the digital signal is set as 30.72MHz to lower the link transmission rate between two devices in the system. At the same time, a RFID reader is integrated in the RU to collect the position information of the RFID tag and send it to MCU. MCU then transmits the localisation information to the remote FPGA in a periodic way. Business data, control data and IoT data are packetised in FPGA and transmitted to the next device through 20km SMF. In the CU, business data and IoT data are depacketised and restored. R&S FSW vector signal analysis (VSA) is used to analyse the restored business data and the application server is used to analyse and process the restored IoT data.

The user-defined protocol used for the data transmission between two devices is in units of basic frames. Each basic frame includes 80 words. As Fig. 3 shows, in each basic frame, the synchronisation word are placed in the 1th and 80th words, the CW is placed in the second word, the business IQ data are placed from third to 65th words, the CM data are placed from 66th to 70th words and the user localisation data are placed from 71th to 75th words. 76th to 79th words are reserved for other services, such as 5G in the future. The protocol can make full use of link bandwidth and the total transmission rate is kept below 6G.

To analyse the performance of the modulated signal transmission of different services of China Unicom with the compressed data rate, we varied the received signal power and measured the EVM of uplink (RU-EU-AU) or downlink (AU-EU-RU), as seen in Fig. 5. We can see from Fig. 5(a) and 5(b) that all the RF channels of both directions have EVM values that are close to each other. The EVM values achieved for the DL and UL directions are as low as 1.3% and 0.5%, respectively. It is seen that under the standard specified by 3rd Generation Partnership Project (3GPP) [17], the downlink dynamic range of the system is more than 30dB and the uplink dynamic range is more than 70dB, which meet the requirement of the MON. These results show that our system is suitable for the transmission of the multi-service low bit rate RF signals.

TABLE I. Frequency Band of China Unicom Services

Service standard	Downlink band	Uplink band	Notes
LTE FDD 1.8G	1830M-1860M	1735M-1765M	MIMO
LTE FDD2.1G	2130M-2170M	1940M-1980M	MIMO
RFID	125K	2.4G	Dual-band

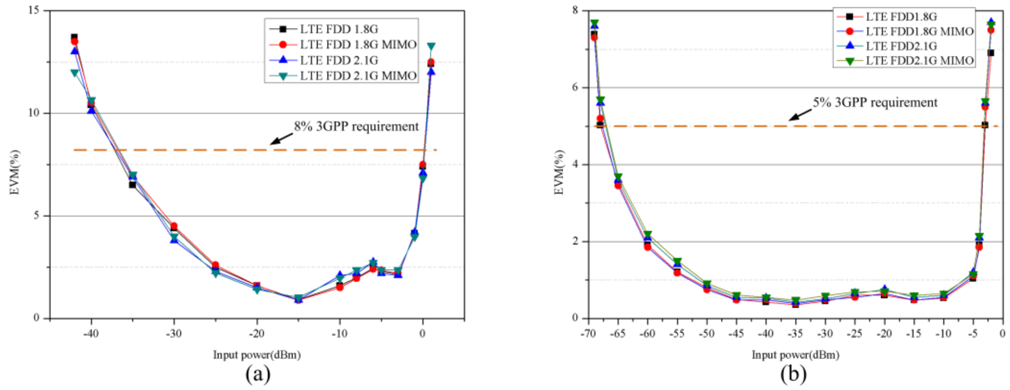

Fig. 5. EVM performance of the China Unicom services transmission (a) downlink (b) uplink

As Fig. 6 shows, an L shaped area in our laboratory is chosen to test the indoor positioning function of the system. The laboratory area is bounded by solid walls which will produce multipath, so it may be considered to be a realistic test environment for real world application. The link between the RFID reader and antenna can be as long as 15m, which allowing the RU to be remote from the antennas. The antennas used in this system are omnidirectional, circularly polarized antennas with a 6dBi gain. Therefore, the DDAS based localisation system can achieve long-distance seamless indoor localisation service converage, and it can improve the detection rate and localisation accuracy by optimizing the position of the antennas. Fig.7 shows the successful tag detection rate as a function of read range over a conventional RFID indoor localisation system and the novel DDAS based localisation system. It can be seen from Fig.7 that the conventional RFID system can only achieve 100% tag read success rate within a range of 2m from the reader, which scales poorly to cover large areas. However, the novel DDAS based localisation system can achieve accurate tag

Fig. 6. Experimental environment of indoor positioning

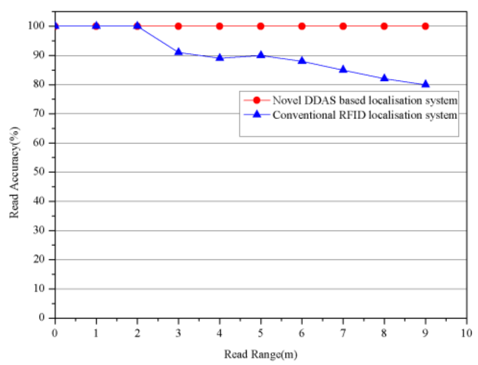

Fig. 7. Tag read accuracy as a function of read range for the novel DDAS based localisation system and the conventional

detection within a large range from the reader. Therefore, the novel DDAS system is capable of enabling a wide area coverage and getting a high localisation accuracy with high reliability. It integrates IoT function on the basis of DDAS with low hardware cost and little interference, which is an ideal solution for IoT function.

IV. Conclusion

In this paper, we have presented an efficient transmission system for Hybrid Fibre-Radio access using DRoF technique that supports multiple channels transmission at low bit rate as well as supporting the increasing services, such as IoT, dynamically. The novel digital signal processing method and the novel fronthaul protocol with high bandwidth efficiency have been implemented in the system. As the experimental shows, all the services of China Unicom can be transmitted in a single <6Gbps optical link with the >70dB dynamic range of the uplink and >30dB dynamic range of the downlink. The RFID services of the system has a 100% detection rate and high localisation accuracy. The system will open up a new business model for future high bandwidth service. Users can customize services according to their own needs. In this way, services are virtualized and separated from hardware system. A new model of mobile service similar to cloud computing is developed.

Acknowledgment

This paper was funded by the international cooperative project of SWIFT (Smart In-building Wireless System using Flexible Digital Transmission Technology). This work was also partially supported by the National Natural Science Foundation of China (No. 61371006), the Equipment Advance Research Project, the Defense Industrial Technology Development Program, and the Chinese Government Fund.

References

[1] D.M.Mathe, B.Neto, R.S.Oliveira et al., “Adaptive Signal Compression in Intermediate Frequency Band for DRoF Mobile Fronthaul,” IEEE photonics technology letters, vol. 31, pp.579-582, 2019

[2] C.H. Liu, L.C. Wang, “Optimal cell load and throughput in green small cell networks with generalized cell association,” IEEE J. Sel. Areas Commun., vol. 34, no. 5, pp. 1058-1072, May 2016.

[3] J. Guo, Y. Liu, X. H et al., “Research on attenuation model of the communication leaky coaxial cable,” in 2017 IEEE 17th International Conference on Communication Technology (ICCT), May 2018. pp.1192-1195.

[4] T. Li, R. V. Penty, I. H. White, “Novel digital radio over fibre for 4G-LTE,” in IEEE Int. Conf. Communication Workshop (ICCW), June 2015. pp. 312-317.

[5] E.A.R. Paixao, R.F. Vieira et al., “Optimized load balancing by dynamic BBU-RRH mapping in C-RAN architecture,” in Fog and Mobile Edge Computing (FMEC), pp. 100-104, 2018.

[6] C. Yoon, D. Cho, “Energy efficient beamforming and power allocation in dynamic TDD based C-RAN system,” IEEE Commun. Lett., vol. 19, no. 10, pp. 1806-1809, Oct. 2015.

[7] F. Tonini, C. Raffaelli, L.Wosinska et al., “Cost-Optimal Deployment of a C-RAN With Hybrid Fiber/FSO Fronthaul,” in IEEE/OSA Journal of Optical Communications and Networking, pp.397-408, 2019

[8] S. Singh, N. Singh, “Internet of Things(IoT): Security Challenges Business Opportunities & Reference Architecture for E-commerce,” 2015 International Conference on Green Computing and Internet of Things (ICGCIoT), pp. 1577-1581, 2015.

[9] C. Bockelmann et al., “Towards massive connectivity support for scalable mmtc communications in 5g networks,” IEEE Access, vol. 6, pp. 28969-28992, 2018.

[10] J. Bae, H. Park, S. Lee et al., “System coverage of Mm wave based 5G mobile communicationsystem,” in the 20th Asia-Pacific conference on communication, April 2014. Pp. 372-375

[11] A. Lometti, C. Colombo, S. Frigerio, and V. Sestito, “Network architectures for CPRI backhauling,” in the 14th Int. Conf. Transparent Optical Networks, Coventry, England, 2012.

[12] T. Li, M. Crisp, R. V. Penty, I. H. White, “Low Bit Rate Digital Radio over Fibre System,” in Proc. IEEE Int. Topical Meet. Microw. Photon., pp. 1-4, Oct.2009.

[13] R. G. Vaughan, N. L. Scott, D. R. White, “The theory of bandpass sampling,” IEEE Trans. Signal Process, vol. 39, no. 9, pp. 1973-1983, Sept. 1991.

[14] Mamatha R. Maheshwarappa, Christopher P. Bridges, “Software defined radios for small satellites,” Adaptive Hardware and Systems (AHS) 2014 NASA/ESA Conference on, pp. 172-179, 2014.

[15] S. Abdollahi, H. S. Al-Raweshidy, T. J. Owens, “Binary-weighted photonic digital-to-analogue converter,” IET Optoelectron., vol. 11, no. 1, pp. 20–28, Jan. 2017.

[16] J. Chen, E. Guan, W. Li et al., “Design of a Novel Automatic Gain Control Method for Digital Communication System,” Navigation and Control, vol. 15, no. 6, pp. 56-61, Dec. 2016.

[17] 3GPP TS 36.304: “Evolved universal terrestrial radio access (E-UTRA); user equipment (UE) radio transmission and reception,” 201