
Heterogeneous cognitive radio sensor networks through RoF-MIMO technologies

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Abstract: Recently, smart grid networks are researched and developed for the greening of the energy consumption. When introducing these into the university or the community, it is required not only the wide area cooperation and the high-speed monitoring & control, but also the construction of the heterogeneous infrastructure with the security and the flexibility. In this paper, recent research on the Radio on Fiber (RoF) technologies are described, and the technology application to the university and/or community smart grid is suggested. And also it is proposed the wide area remote connection of heterogeneous cognitive radio networks by RoF-MIMO (Multiple Input Multiple Output) technologies. Network throughput and the network outage rate using various types of RoF-MIMO systems are calculated and compared. And it is shown that the distributed parallel RoF-MIMO can improve the throughput and the outage performance simultaneously. Prototyping Experiment is also conducted in the faculty building and confirms that the network outage is improved by the distributed parallel RoF-MIMO.

Keywords: Wireless Sensor Networks, RoF-MIMO, Smart Grids, Heterogeneous Networking

1. Introduction

Smart grids using wireless sensor networks are key issue to establish an ecological and sustainable society. Recently, cognitive radio sensor network (CRSN) technology has been proposed to solve the radio spectrum utilization problem. [1] This technology is now considered to be the wireless ad hoc networks, because the smaller cell spectrum sensing and operation is effective to find the spectrum hole and slots. It has the higher performance comparing with the macro-cell operation. However ad hoc small cell networks have some problems in global extension of the heterogeneous system operation such as community networks. For the CRSN in home and/or business office, the uniform wireless system construction is available, because the single owner decides and conducts the equipment installation in their own facility. On the other hand, in the small community grids, such as a big mall, university and multi-vender integrated manufacturing farm, various and different types of the sensor terminals and the mobile terminals are gathering at the same place. In such a small community, heterogeneous and cognitive wireless

sensor networks and several types of smart grid equipment are installed. Small number of wireless sensors of single network is distributed in the wide area through different groups of networks, like sandwich structure. Then, it becomes difficult to establish wide area sensor networks by using heterogeneous wireless sensor terminals, because the sensor density of reachable terminal becomes thin and the signal becomes unreachable.

For the efficient and highly reliable use of the heterogeneous CRSN, we propose to establish the virtual radio free space transmission using the Radio on Fiber (RoF) technologies [2]-[4]. The conceptual illustration of the virtual radio free space transmission with radio agents is shown in Fig. 1. This infrastructure supports not only the CRSN but also the total operation of the heterogeneous radio systems cooperation by the Agent Based Communication Protocol (ABCP) [5]-[8].

In this paper, Section 2 describes the Radio Free Space Transmission using the RoF-MIMO (Multiple Input Multiple Output) system [9]-[28]. Also RoF-MIMO is categorized into four types, i.e. the Serial RoF-MIMO, the Parallel RoF-MIMO

with terminal connection, the Parallel RoF-MIMO with distributed connection and the DRoF-MIMO (Digitally connected RoF-MIMO). Final part of Section 2 proposed the conceptual system of smart grids for small community and compared with the smart grids for Home and/or Office. Section 3 analyzes the performance of CSRN with/without RoF-MIMO systems, such as network outage probability and the throughput performance. RoF-MIMO performances are

theoretically calculated and compared among the every type of RoF-MIMO systems and also the system without RoF-MIMO. To confirm the performance, the prototype system experiments are conducted in MJIT, UTM building. Section 4 shows the prototype experimental setup and obtained results. In the final section 5, RoF-MIMO technologies for antenna multiplexing are classified and compared.

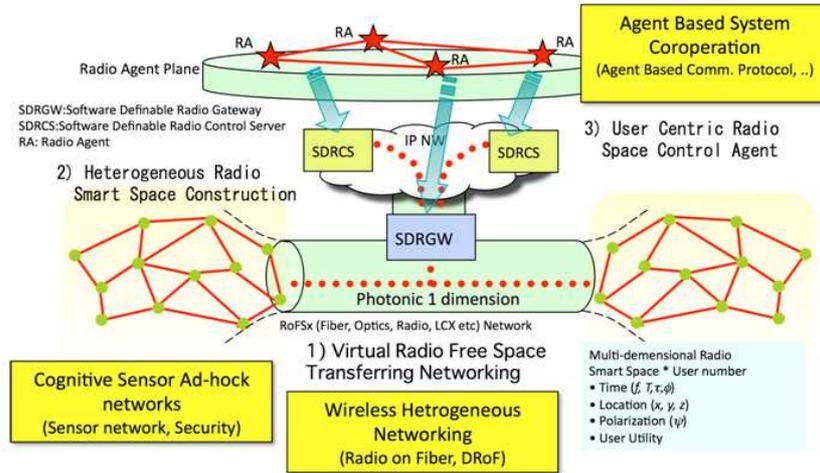


Figure 1. Conceptual illustration of the total configuration of the virtual radio free space with Radio Agents.

2. RoF Applied to the Heterogeneous Cognitive Radio Sensor Networks

2.1. Virtual Radio Free Space Transmission

In Fig.2, CRSN and their Virtual Radio (VRa) Free Space transmission to other place is shown. VRa is realized by using the RoF-MIMO technology, such as [9]. RoF-MIMO technology requires multiple input-antenna and output-antenna at the both side of the optical fiber. To reproduce the radio space at the other side, radio space that has multiple parameters of Time (frequency, frame, time-slot, phase), Location (3 dimensional coordinates) and radio wave polarizations are translated into one dimensional fiber space, by using various types of RoF technologies shown in Section 5.

MIMO technologies are classified into two types, i.e. single-user MIMO and multi-user MIMO. In case of CRSN, latter multi-user MIMO is utilized, so RoF-MIMO should provide the multi-user MIMO function.

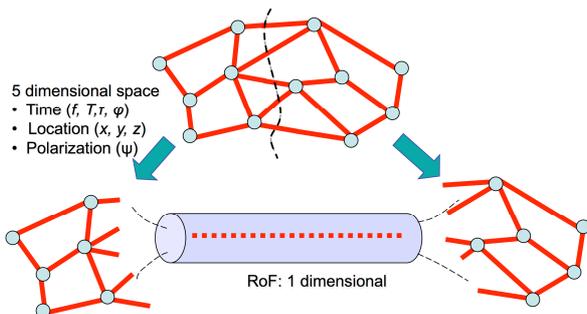


Figure 2. Cognitive radio sensor networks on RoF-MIMO system.

2.2. Various Types of RoF-MIMO Systems

RoF-MIMO systems are classified into the following types, as shown in Fig.3.

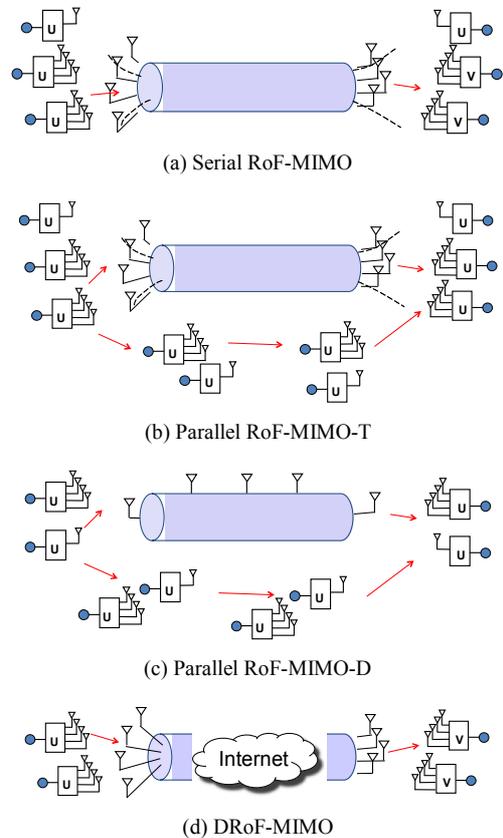
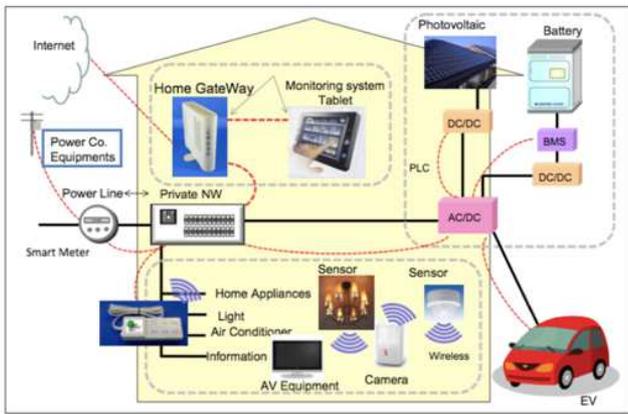


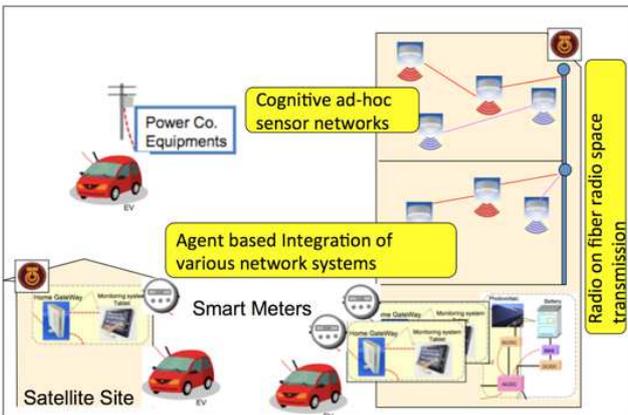
Figure 3. Classification of RoF-MIMO systems.

Serial RoF-MIMO is used for a remote site connection, i.e. the function of CRSN area extension. Parallel RoF-MIMO with terminal connection type (Parallel RoF-MIMO-T) is utilized for the congested area bypassing to ease the spectrum sensing and radio interference reduction. The parallel RoF-MIMO with distributed antenna (Parallel RoF-MIMO-D) is utilized for the multi-point connection. DRoF-MIMO is utilized for radio space transmission by digital pulse format through internet or digital broadband networks. In this case radio signals are band-pass sampling and digitized at the input port. At the output port, radio signals are reproduced by D/A conversion of digital data. In this case, long distance connection of radio space is available, and normally used for serial connection of separate CRSNs.

2.3. Configuration of the Smart Community Grids



(a) Smart Grids for Home and/or Office



(b) Smart Grids for Community or University

Figure 4. Smart Grids for Home and for Community.

In this section, configurations of the smart grids for home and for community are shown and compared. Some required characteristics for the smart grids for community are shown. Possibilities of the system performance improvement by the RoF-MIMO system will be mentioned. Figure 4 shows the conceptual illustration of smart grids for home and for community. Application example for a home and/or office is shown in Fig. 4 (a). Unified sensor element and equipment can be implemented in the small area, and it is easy to setup

ad-hoc network with the unified network elements. All sensors can easily connect every adjacent terminal. On the other hand, in case of the smart grids for community shown in Fig. 4 (b), networking area is widely spreading and heterogeneous sensor, that is different types of groups and air interfaces, are implemented. As the results, it is difficult to establish the ad-hoc sensor networks among the different types of adjacent terminals. The parallel RoF-MIMO-D, that has multiple of antenna elements in single fibers, can easily extend the virtual free space to remote site and setup spreading networks using distributed sensor elements.

3. RoF-MIMO Performance

RoF-MIMO performance is theoretically analyzed on the network throughput and the network outage probability, considering with the various configuration of RoF-MIMO system as shown in Fig.3. Calculated results are compared with that of without RoF-MIMO. System parameters used in this analysis are notated as follow.

N_{mimo} : Number of antennas of RoF-MIMO

L : Maximum network length

D : Diameter of the cell, i.e. reachable area of each cluster of sensors

B : Bandwidth assigned for the wireless sensor networks

R : frequency reuse distance

N_t : Number of total wireless sensor terminals

P_t : Probability of wireless sensor terminal in active

3.1. Throughput Performance of RoF-MIMO System

Throughput performance of each terminal without RoF-MIMO Th and with RoF-MIMO Th_{mimo} are as follow,

$$Th = \frac{B}{R N_t D/L}$$

$$Th_{mimo} = \frac{B}{R N_t D/L} \left(1 + \frac{N_{mimo}}{L/D}\right)$$

Last term of (2) indicates the throughput improvement factor by RoF-MIMO system. This comes from that the total throughput increase N_{mimo} is shared by every cell, i.e. N_{mimo} divided by the number of cells L/D . The name of cell means the cluster of sensor terminals. In the cluster, every sensor terminal shares the same frequency band. Adjacent cell utilizes another frequency band to prevent interference among adjacent cells. Frequency reuse distance R is introduced to prevent interference among adjacent cells. Throughput performance is as same as for RoF-MIMO-T and RoF-MIMO-D, because the throughput increase is proportional to number of MIMO antennas N_{mimo} in the ideal case. Calculated results are shown in Fig.5 As is seen in the figure, throughput of each sensor terminal decreases as the number of terminals increases. And it increases when the number of the cell L/D increases. RoF-MIMO improves the throughput, however the improvement will decrease when the diameter of cell D increases.

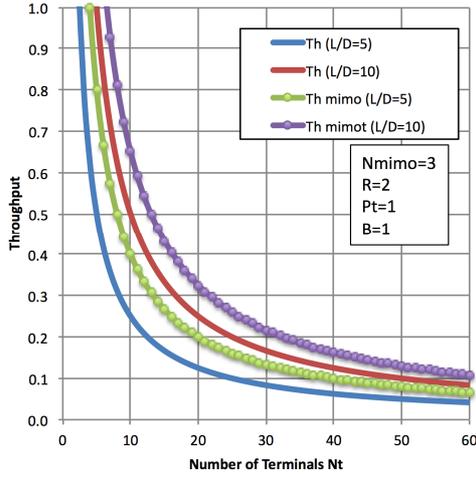


Figure 5. Throughput performance of RoF-MIMO

3.2. Network Outage Rate Improvement by RoF-MIMO

Network outage happens when the link among the sensor terminals is not reachable. In this analysis, it is assumed that the cells are series-connected in the sensor networks, and the network outage happens when any one of cells in the networks does not have any sensor terminal. Network outage probability is calculated as follows.

$$P_{out} = \frac{L}{D} \left(1 - \frac{D}{L} P_t\right)^{N_t}$$

$$P_{out,mimo-T} = 2 \left(\frac{L}{D} - 2 N_{mimo} - 1\right) \left(1 - \frac{D}{L} P_t\right)^{N_t+1}$$

$$P_{out,mimo-D} = N_{mimo} \left(\frac{L}{D N_{mimo}} - 1\right) \left(1 - \frac{D}{L} P_t\right)^{N_t+1}$$

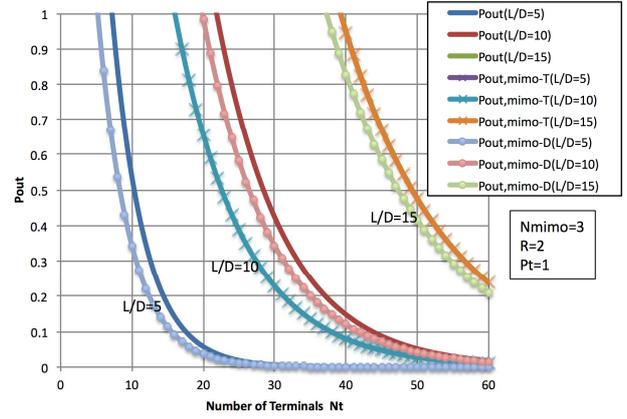
where, P_{out} , $P_{out,mimo-T}$ and $P_{out,mimo-D}$ denote the network outage probability of the without RoF-MIMO, with the RoF-MIMO-T and the RoF-MIMO-D, respectively. In this analysis, terminal distribution is uniform in the single dimensional space 0 through L . And it is assumed that the probability of wireless sensor terminal in active state $P_t = 1$. This means that all the sensors are power on and exist in the area of 0 through L .

Calculated examples of network outage probability are shown in Fig.6. As is seen in Fig.6 (a), the network outage probability decreases as the number of terminals increases. The RoF-MIMO system can improve the network outage probability. Improvement factor decreases when network length L/D becomes large. The RoF-MIMO-T is superior in case of network length is short. The RoF-MIMO-D is superior in case of network length is large.

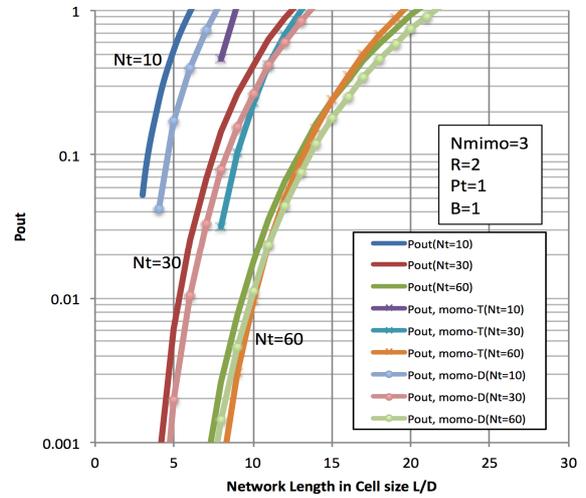
Figure 6 (b) shows the calculated network outage rate vs. network length, and it clearly shows that the ROF-MIMO-D is better than the RoF-MIMO-T.

Figure 6 (c) shows the improvement of network outage rate vs. number of the parallel RoF-MIMO-D stage N_{mimo} , i.e. number of antennas in RoF-MIMO-D. It shows that the outage probability is improved in proportional of N_{mimo} . It may be easy to increase N_{mimo} in case of the RoF-MIMO-D system, by

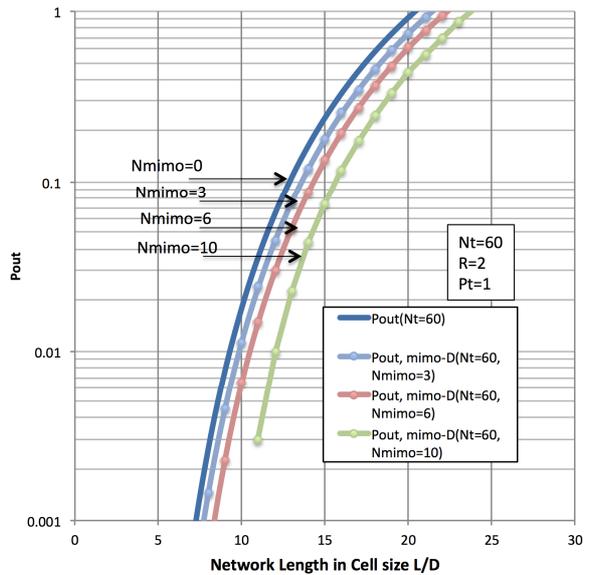
using the optical star coupler.



(a) Network outage rate vs. Total number of terminals



(b) Network outage rate vs. normalized Network length



(c) Network outage rate and RoF-MIMO-D dimension N_{mimo}

Figure 6. Improvement of network outage rate by RoF-MIMO system

4. Prototype System Experiments

4.1. Experimental Setup

Configuration of the prototype system setup is shown in Fig. 7. This includes heterogeneous power monitoring system and heterogeneous wireless sensors.

Experimental equipment is shown in Fig.8. Specification of

equipment used for experiments is also shown in Table 1. E/O and O/E equipment is from Stack Elec. Inc., and 1:2 star coupler is from Fiber Optic Communication Inc. Wireless sensor terminals are based on the ZigBee based terminal, fabricated by Digi and Texas Instruments. Used software is Smart RF Studio 7 and XCTU v.3.8 supplied by Texas Inc. and Digi, respectively.

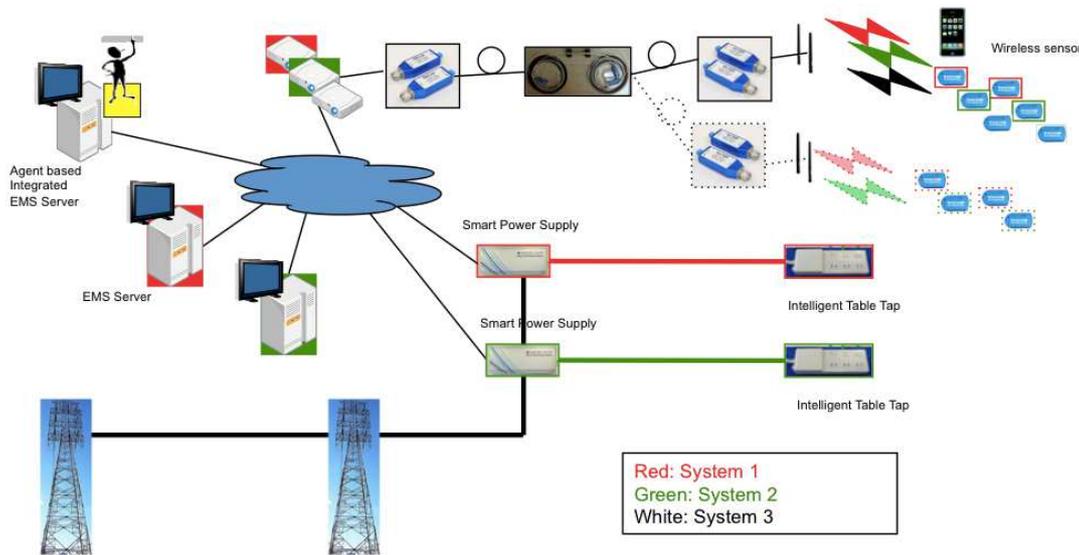


Figure 7. Configuration of the prototype system.

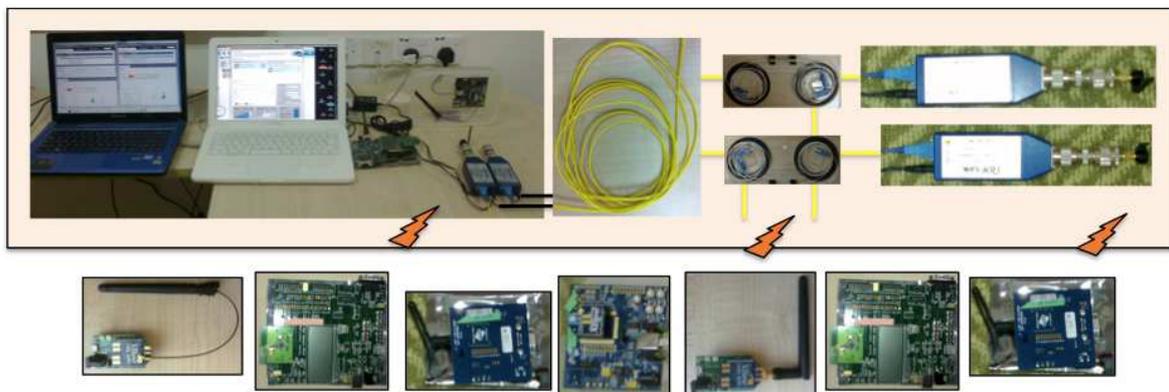


Figure 8. Equipment used for the parallel RoF-MIMO Experiment.

Table 1. Specification of the Experimental Equipment

Continued table 1.

Wireless Sensors	
Digi ZigBee RF Development Kit	
XBee-Pro SMA module: XBP24BZ7CIT-004	
XBee-Pro Wire module: XBP24BZ7WIT-004	
XBee-Pro PCB module: XBP24BZ7PIT-004	2.4GHz
XBee-Pro UFL module: XBP24BZ7UIT-004	ZigBee
XBee-USB interface: AE-XBEE-USB	Pout = +0 dBm
Xbee USB interface board: XBIB-U-DEV	9600 bps
Xbee RS232C Interface Board: XBIB-R-DEV	
Software: XCTU v3.8 Mac	
TEXAS CC2520 Development Kit	
CC2520EM 2.1	2.4GHz
SMART RF05 EB	ZigBee
Software: Smart RF Studio 7	Pout = +0 dBm
	9600 bps

RoF Module	
E/O,O/E Module	Opt Pout = +6dBm +- 0.5dB AGC: Pin +6dBm to -1.5dBm CNR > 63 dBc @ BW10kHz IM3 > 53 dBc @ Pout 0dBm Gain = 0dB +- 4dB
Stack Electronics: E/O: ROF102(E/O)	
Stack Electronics: O/E: RoF103(O/E)	
1:2 Splitter	
FOCI:	insertion Loss: 4dB @1550nm
O-TS-LH-102-10/10-WB-SC/SC-4-A	return Loss > 55dB
Fiber Cable	
Corning: SM-2Z-SCSC-30	Single Mode
	Loss 0.09-0.14dB

Experimental measurement to confirm the parallel RoF-MIMO-D performance is conducted in the MJIT UTM Faculty building at level 5, and the floor map is shown in Fig.9. Total length of the networks is around 100m. Optical fiber is installed at the end point of the network, i.e. RoF-MIMO-D with $N_{\text{mimo}}=2$. Number of XBee terminals is 6 and their MAC addresses are indicated in the figure. Source terminal is 5D85C and the destination terminal is E083B, and packets are sent from source to destination.

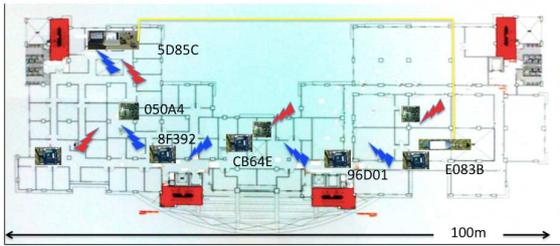
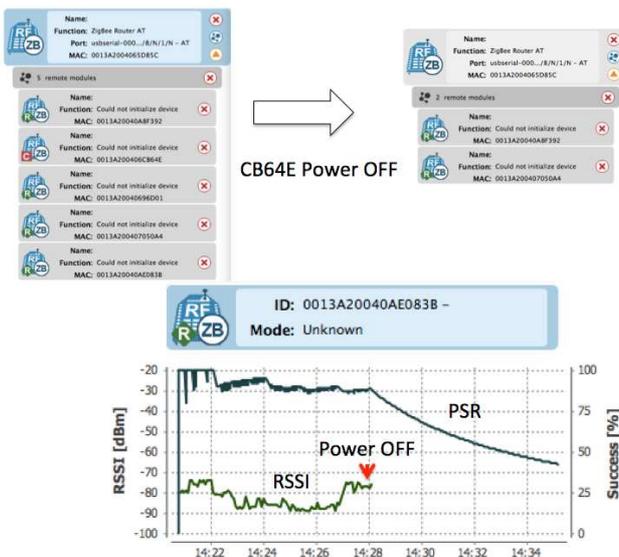


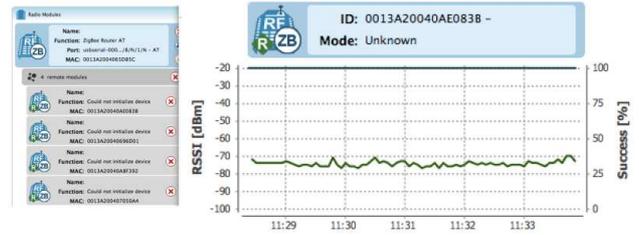
Figure 9. Experiment site map in the MJIT level 5.

4.2. Experimental Results of Wireless Sensor Networking

Packet success rate (PSR) are measured by using the range test module of XCTU software. Measured results are shown in Fig. 8. It shows networked terminal information list. Also the average PSR in % and the local received signal strength indicator (RSSI) in dBm are shown in the graph format. Fig.10 (a) shows the wireless sensor network performance without RoF-MIMO-D, before and after the CB64E terminal power is OFF. After the terminal power is off, RSSI becomes low and averaged PSR gradually reaches zero, i.e. PSR becomes zero. After the CB64E power is off, networks are reconfigured, and the indicated terminal list includes only two terminals. Fig. 10 (b) shows the measured PSR and RSSI with RoF-MIMO-D. PSR are 100% and the RSSI is stable, even if the terminal CB64E is power off, because the end-to-end terminals are connected through RoF-MIMO-D system.



(a) Before and after the CB64E Power OFF, w/o RoF-MIMO-D

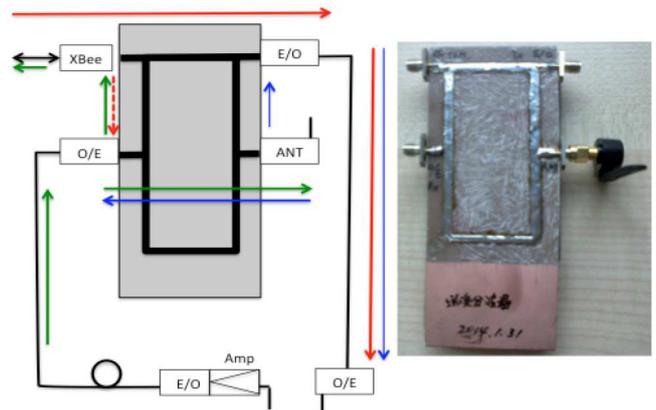


(b) Before and after the CB64E Power OFF, w RoF-MIMO-D

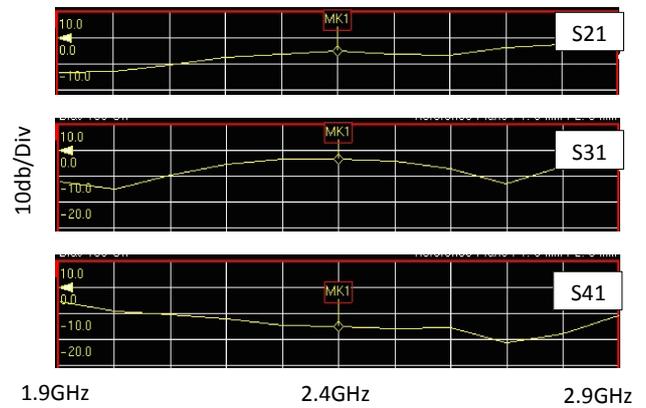
Figure 10. Experimental result of Sensor Networking Availability

4.3. Antenna Duplexer for RoF-MIMO System

Air to air connection by RoF-MIMO generates large coupling loss between the nearest wireless sensor terminal, and the RoF E/O O/E converters, due to the propagation loss among them. To prevent the propagation loss, one wireless sensor are directly connected to the hybrid coupler shown in Fig.11. Measured coupling loss between port 1 to port 2, i.e. S_{21} , port 1 to port 3, i.e. S_{31} , and isolation loss between port 1 to port 4, i.e. S_{41} are shown in the same figure. As is shown, coupling loss becomes lower than 5dB, and improved by more than 10dB comparing with the conventional air inter face.



(a) Coupler Configuration



(b) Coupling and isolation loss of every port

Figure 11. Configuration and measured performance of antenna duplexer

5. RoF-MIMO Technologies for Antenna Multiplexing

To realize RoF-MIMO system, it is required to multiplex multiple of antennas in one fiber cable. RoF-MIMO transmission technologies are classified according with the multiplexing methods and networking methods. Recently, as the various research and development on photonic networking and switching has been conducted, these analogue type technologies are applicable for RoF transmission of several

radio frequency (RF) signals from multiples of antenna. Also, fast sampling of RF signals are applicable, such as band-pass sampling and is referred as DRoF-MIMO. Examples of classification are follows. Comparison and some configurations are shown in Table 2 and Figures 12-14.

- (a) Optical Sub carrier multiplexing (SCM) and WDM
- (b) Optical Time Division Multiplexing (TDM) and Natural Sampling
- (c) Direct Switching Optical Code Division Multiplexing (DOS-CDM)
- (d) Digital RoF and Band-pass Sampling

Table 2. Classification of the optical multiplexing

Multiplexing Scheme	Advantage	Disadvantage
Optical Time Division Multiplexing (O-TDM)	IM/DD link configuration is available Photonic time switch routing is available No Optical beat noise interference	Fas Fast photonic switch is required Time synchronization among radio station is required Time
Subcarrier Multiplexing (SCM)	Intensity Modulation/Direct Detection (IM/DD) link is available	Optical beat noise is generated Radio spectrum allotment and control is required Direct photonic routing can not available Optical wavelength efficiency becomes low Wavelength filters are required Wavelength photonic routing is required
Coarse Wavelength Multiplexing (C-WDM)	IM/DD link is available	Coherent photonic source is required Narrowband optical filter is required Wavelength photonic routing is required
Dense Wavelength Multiplexing (D-WDM)	Effective use of optical wavelength is available Robustness of fiber dispersion if SSB is utilized High receiver sensitivity, when coherent detection is utilized	
Optical Code Division Multiplexing (DOS-CDM)	Easy realization using Direct Optical Switching CDM (DOS-CDM) is available No time synchronization is required	Balance photonic detection and Optical Polarity Reversing Correlator (OPRC) are required

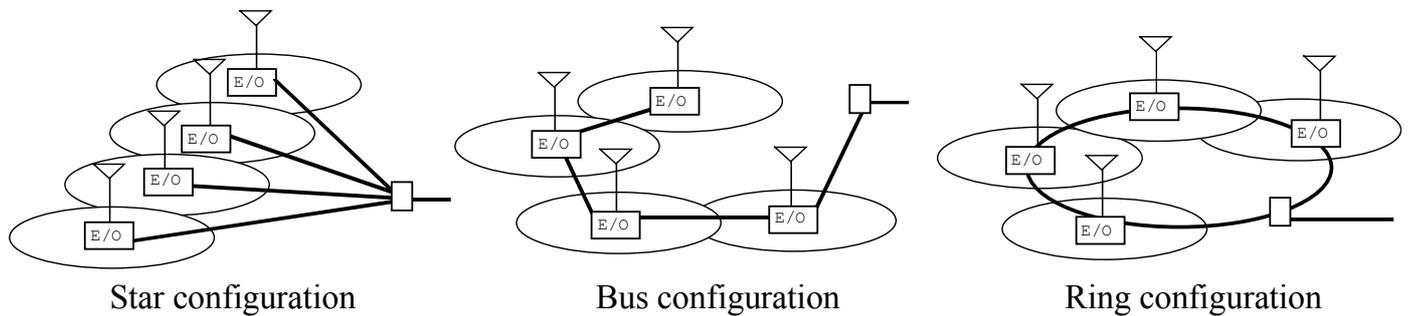
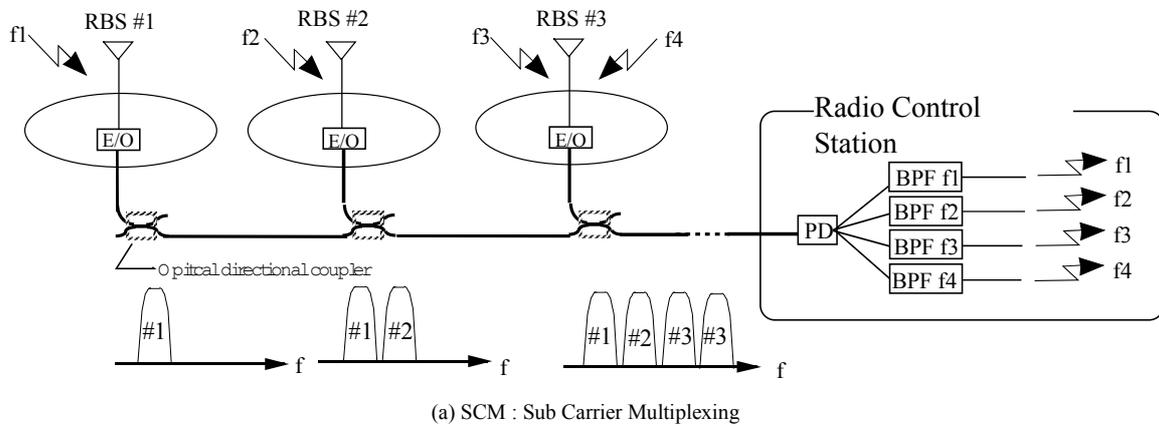
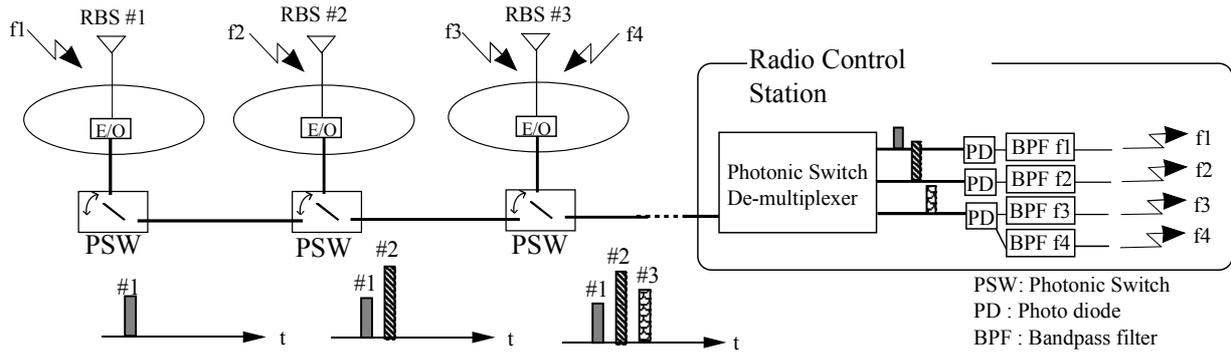
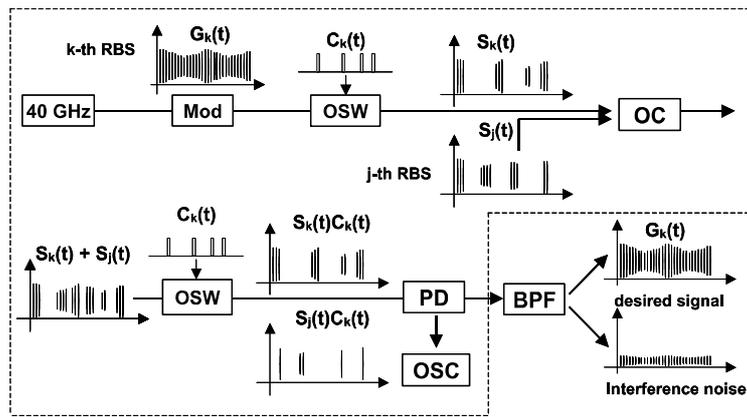


Figure 12. Classification of Network Configuration.





(b) O-TDM : Optical Time Division Multiplexing



(c) DOS-CDM: Direct Switching Optical CDM

Figure 13. Configuration Examples of Optical Multiplexing

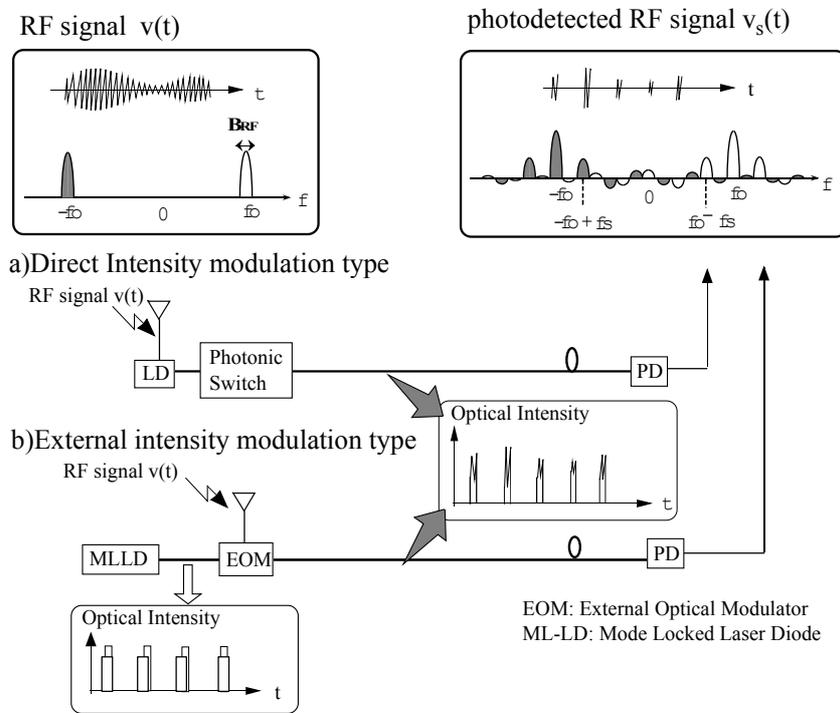


Figure 14. Principle of Bandpass Sampling

6. Conclusion

In this paper, RoF-MIMO application to the Smart Grids for community is investigated and the Virtual Radio Free Space connection of Cognitive Radio Sensor Networks is proposed. This connection utilizes the RoF-MIMO system, and the systems are classified into four types. Network outage probability and the throughput performances of every type are analyzed and calculated theoretically and compared. Results show that the network outage probability and the system throughput, i.e. simultaneous user capacity, can be improved by using the parallel ROF-MIMO with distributed connection. To confirm the theoretical result, experiments using the prototype wireless sensor terminals are conducted in the faculty building and confirmed that the Parallel RoF-MIMO with distributed connection can relieve the network outage. In the final part, various types of MIMO antenna multiplication methods are introduced and the advantages and disadvantages are compared.

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