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Design and testing of a cluster-tree topology networking protocol over cost effective non-standard RF module

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Abstract: This paper demonstrates the experimental result of a wireless network using the proprietary low cost and low power NRF24L01+ radio module. The wireless network can theoretically connect up to 65,000 nodes using low power, moderate transmission rate but have high quality of service communication and negotiable range compensating power consumption (Link budget). To the best of our knowledge, this is the first time such network has been implemented. The network consumes very small power compared to other standards such as ZigBee, and Bluetooth LE. The paper describes the protocol used for the network and the test results for number of nodes connected with a sample application of the network. The intended application includes but not limited to lighting array network, low power sensor nodes for IoT, wireless bootloader, garden control, home automation, etc.

Keywords: RF communications, networks, nrf24, IoT, wireless networks

I. INTRODUCTION

Choosing the right wireless communication solution can vary based on their intended application, where the design has to be optimized for either data rate, range, low power consumption, cost or reliability. Considering the scenario where high data rate is not a significant factor, neither interoperability between devices are necessary, protocols such as IEEE 802.15.4 can be relatively costly[1]. Also, maintaining compliances with standards sets asides many physical limitations. An Alternative radio module available is the low cost, low power NRF24L01+ by Nordic Semiconductors[2]. It uses a proprietary protocol and does not support standard addressing in the link layer. The NRF24L01+ are intended to be used as a star topology for Human Interface Devices (HID) such as mouse/keyboard, or even wireless headset since it can support a data rate up to 2Mbps[2]. This gives the potential to design a custom network. A cluster-tree -network design has been proposed and their performance has been monitored. The networking features a theoretical support of 65536 nodes due to the 2-byte network addressing field. Each node is a repeater, and contains its own routing table. Network nodes can send back acknowledgement back to the source node. The routing table of the intermittent nodes assigns the path of data from source to the destination. This ensures only one true path of the packet to travel through. Fig. 1 shows the two-common variety of the breakout board using the NRF24L01+. The breakout board with the power amplifier provides a theoretical range of 1 km as line of sight. All the experiment and testing done are using the model with the power amplifier model. However, both the models are a drop-in compatible. If we are sure of two adjacent nodes to have a distance less than 30 meters[3] .

Fig. 1.The NRF24L01+ breakout board. The Left is the official design provided by Nordic Semiconductor, and the right is the version with Antenna amplifier for longer range.

II. COMPARING THE RF SOLUTION WITH OTHER STANDARDS

A. Standards and Modulation Comparison

ZigBee and Bluetooth LE are IEEE standard protocols which gives high reliability for commercial and industrial usage [4][5][6]. Much of design effort is needed to ensure compliance with the standards. The standards are great when interoperability between devices are necessary for compatibility. For applications, such as switching, garden controls, ambient sensors, etc. where communications occur between long intervals and low data speed is sufficient, adoption of standards such asZigBee and Bluetooth are costly.

ZigBee uses Q-QPSK modulation whereas Bluetooth LE and NRF24 uses GFSK modulation. NRF24 does not use spread spectrum scheme and features an automatic retransmission for packets for which an acknowledgement was not received. It transmits a packet on a single frequency and it stops and waits for an acknowledgement. The NRF24 can relocate its carrier frequency by changing a single register value as an offset to 2400Mhz. However, for the nodes to communicate, same carrier frequency must be assigned.

The NRF24L01+ has a receiver sensitivity of -94dBm at 250kbps[2]whereas ZigBee has a receiver sensitivity of -92 dBm for the same data rate. LoRa offers the best sensitivity of -137 dBm allowing communication over several kilometers.

B. Power consumption, Range and Data Rate

The NRF24 consumes very low power, even lower than the ZigBee and can run on a single coin battery for several months to a year [1].Also, the length of activity per 8mS is only 558us in the NRF24L01+ compared to the ZigBee taking 1772us. The idle state current consumption in the NRF24L01+ is only 10.2uA whereas ZigBee and BLE is significantly higher with 351uA and 15mA respectively. The power down state of the NRF24L01+ is only 400nA compared to ZigBee consuming 20uA. If the NRF24 is intended to be powered via DC power source, then the module variant with a power amplifier (PA) can extend the communication range to about 1Km [7][3].

The ZigBee and BLE offers data rate in a few kbps to less than 1Mbps. NRF24 can provide a data rate of 2 Mbps[8][9]. However, upon implementing the networking layers, the actual rate will be less than 2 Mbps, due to expected packet losses and overhead data that are encapsulated in the payload. In addition, the overhead data processed by the can introduce further delays.[10]

C. Networking Support

The ZigBee have standard support for true mesh networking[11]. Being a standard, the platform stack supports the MAC layer and PHY layer. Bluetooth LE supports official meshing topologies such as point to point, broadcast and mesh. The NRF24L01+ is optimized for peer to peer or a star network as it features the Multiceiver™ (a hardware feature of the NRF24L01+ radio) that enables to receive on 6 parallel data pipes with unique addresses [10]. To extend the network capabilities, the payload of the NRF24L01+ radio module must compromise some bytes to hold the packet information along with the actual data to be sent over the network.

III. THE NETWORK DESIGN ON NRF24L01+

The module is developed by Nordic Semiconductor and its protocol is proprietary and operates at 2.4 GHz ISM bandwidth. The data rate supported is 250kbps, 1Mbps and 2Mbps. It is a low power consuming module and inexpensive compared to other IEEE standard protocols such as ZigBee.

The hardware can send a payload of 32 bytes encapsulated in a single packet. It also features, variable length detection, 8/16-bit CRC and acknowledgement to the sender. Each module has 6 parallel receivable pipes, each with its own 5-byte address. Any other node can send to any of the 6-receivable pipe of the node simply by modifying the 5 bytes transmit address. This feature of receiving in parallel from multiple pipes is termed as Multiceiver™ by Nordic which is implemented in the hardware of the radio module.

Fig. 2 illustrates an example to show how the radio can have 6 parallel receiving pipes, each with its own 5-byte address and another node can set its transmission address to send to a specific pipe. Node A has its own 6 RX pipe address defined, so does node B. If Node A wants to transmit a data to pipe 4 of node B, then all it needs to do is set the 5-byte address of node B’s pipe for address, i.e. (0xE7C2E7C2C4).

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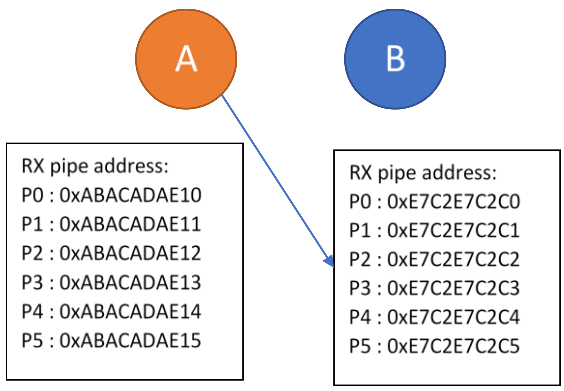

Fig. 2. Two Nodes, each consisting of 6 parallel receiving pipes with their own 5 byte address. If node A wants to send data to a specific pipe on Node B, it needs to set the Tx address to the 5 byte address of that pipe on node B.

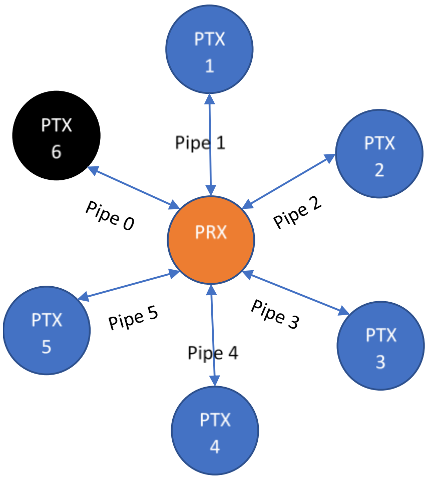

Fig. 3. The Multiceiver(TM) is the feature that allows one node to have 6 parallel receiving pipes. (Source: Nordic Semiconductor NRF24L01+ datasheet)

When Node B receives a payload on its 4th pipe, then the status register of the node will have the value of the pipe number of the last received payload (i.e. 4) This addressing can be used to create a single star network, mostly suitable for one single receiver to have multiple transmitting nodes (e.g. An USB dongle for HID mouse keyboard, where both mouse and keyboard sends data to the single receiver), as shown in Fig. 3.

When a node wants to transmit a payload to another node and expects an acknowledgement, then it needs to make sure that the TX address is equal to the Pipe 0 address. This is because, when the module sends the packet on air, it immediately switches to RX mode and expects an acknowledgement payload on pipe 0. Hence whenever we plan to use acknowledgement feature, it is better to not use pipe 0, since its value changes every time we send data to a different node.

IV. MODE OF OPERATION OF THE NETWORK DESIGN

Our proposal is to extend the network and not limit it to a star network, with the objective of using it to send short messages through the nodes at low data rate. Such as controlling lighting/equipment's, garden controls etc. When the area gets wider, the range between nodes can be expanded. In that case, we expect reachable intermittent nodes to forward messages from source node to destination node. The different features of the network are explained below. Real payload data sent between nodes does not necessarily have to pass through the coordinator node, however, their connectivity status is registered in the coordinator node.

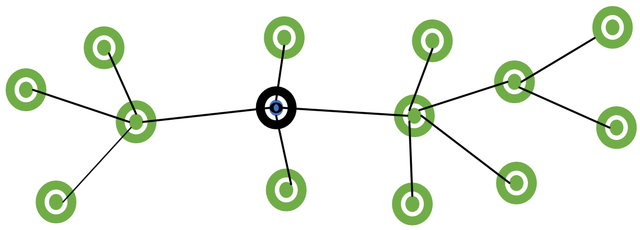

Fig. 4. A tree network with a centralized coordinator node.

A. Each node as a forwarder

Each intermittent node acts as a forwarder. The nodes will have its own routing table and will remember which adjacent node leads towards the destination node. This happens under two scenarios where the node updates the routing table. The friend node is defined as the closest node already connected to the network. All intermittent nodes will remember which adjacent nodes it must forward the packet to, so the packet can find its way to the destination node. The illustration below in Fig. 5 shows how intermittent nodes (node A and B) forwards a packet.

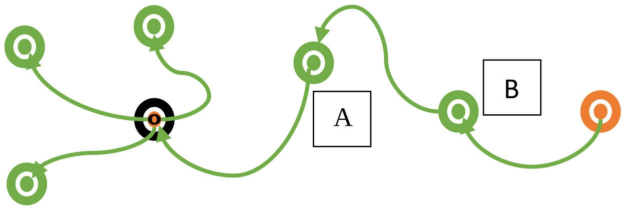

Fig. 5.Illustration of how intermittent nodes (A and B) are forwarding payload from the orange node towards the coordinator

When an intermittent node receives an acknowledgement from the destination node back to the source node, it confirms the adjacent node via which the acknowledgement packet has been received and registers in the routing table. Fig. 6 illustrates such an example. Node B wants to send a data to node M and node M sends an acknowledgement back to Node B. The intermittent nodes in the path consists of node A, node K, node L and the coordinator. When node K and node L receives the packet from node B, it registers the path (i.e. adjacent node) in its routing table so it remembers the path that leads to node B. For the next time for example if node L receives a packet where the destination address is node B, then it will forward the packet to node K, since it knows that node K is the adjacent node that leads the path towards node B.

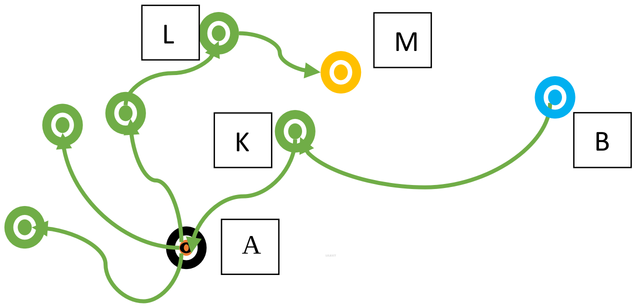

Fig. 6.The figure demonstrats the communication happeningbetween Node M and Node B and how the intermittent nodes behaves.

B. Node address assignment by the coordinator

The proposed network will require one coordinator node. When new nodes join the network, they communicate with the coordinator node and is assigned a network address. Each node can have up to 5 adjacent nodes, of which one node directs towards the coordinator node. When a new node wants to join the network and its prospective adjacent node is not the coordinator, then the node at reach (friend node) send request on behalf of the new node to the coordinator for it to assign an address. The coordinator registers the new node and replies the assigned address. The friend node will register the new node as its adjacent node and the new node will be aware of its own assigned address.

C. Adjacent nodes addressing mechanism

Each of the parallel pipes of the radio module has unique address, 5-byte wide that is used to communicate with the adjacent nodes. This means a node can identify on which pipe it has received a payload into, and correspond to the adjacent node that has sent the network payload. This is great for establishing a star network. But over a larger network, the network address of the source and the destination must be encapsulated in the link layer payload supporting 32 bytes (as seen in TABLE I.). It makes more sense if the address used for the network, i.e. the network ID and the node ID are embedded in this 5-byte hardware address. This will make it easier to identify adjacent nodes, process the routing table, finding path towards the coordinator, and checking whether the destination address matches its own. 2 bytes are required to hold the network ID and another 2 bytes for the Node ID. This allows a theoretical support of 65536 devices including the coordinator node. As planned, each node can hold up to 5 adjacent nodes, the pipe number can also be embedded into the address. The overlapping of the network address information on top of the link layer hardware address is shown in TABLE II. Note that, the hardware address is not readable by the radio, but the status register of the radio can identify which pipe the payload has been received. Also, note that, the hardware address is only used when one node wants to communicate with its adjacent node. This means the network address of the source and destination must still be encapsulated within the 32-byte payload.

TABLE I. NETWORK ADDRESSING FORMAT IMPLEMENTED

	Byte 4	Byte 3	Byte 2	Byte 1	Byte 0
Link	RX address [4:0]				
Network	Network ID		Node ID		Pipe no

D. Packetization

As seen in the section "NRF24L01+ module", each radio module can send a maximum of 32 bytes to another adjacent radio node. This means that if we want to implement a network Application Programming Interface (API), all the network header information must be encapsulated within the 32-bytes payload. The packer header information needed in the proposed network consists of the destination address, the source address, the packet information, PID, and actual network payload, as seen in Fig. 7.

The hardware of the radio module feature 6 parallel pipes with unique addresses. The address of each pipe is 5 bytes wide. The assignment of the address in the design utilizes networking knowledge. This will require the 5 bytes to be broken down into a patter containing information such as network address, node address and the pipe number. The width of each of this information is described inTABLE II. .

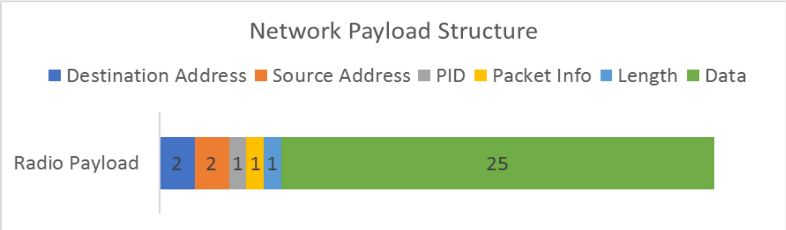

Fig. 7. The breakdown of the 32-byte maximum payload implementing the network structure, consisting of the destination address, source address, PID, packet info and the data.

TABLE II. NETWORK PAYLOAD STRUCTURE

bytes	No of bytes used	Usage
[31:30]	2	Destination Address
[29:28]	2	Source Address
[27]	1	PID (Packet Identification)
[26]	1	Packet Info and Status
[25]	1	Length of Data
[0:24]	25	Data

The header occupies 7 bytes of data, leaving a space of 25 bytes to send data over the network. The source node address and destination node address has a width of 2 bytes, which means, theoretically, we can support 65536 nodes each with its own ID.

The PID is used for packet disassembly and reassembly in case the data to be send has a size of more than 25 bytes. However, current design does not support packet disassembly and reassembly but can be implemented in the current API or higher-level API in the future.

E. Routing and Forwarding

The proposed method to route the gateway in each node to act as a repeater is to remember the adjacent node through which routes towards the destination node[10]. When a new node requests an address from the coordinator, the intermittent nodes also registers this new node in its own routing table. Whenever it receives a network payload, it checks if the destination address is found in its routing table. If so, it forwards to the adjacent node that is assigned against the destination address. If not, it forwards to all the adjacent nodes. If the destination address matches that of the nodes own assigned address, it simply keeps the node. The flow chart for the routing table is shown in Fig. 8.

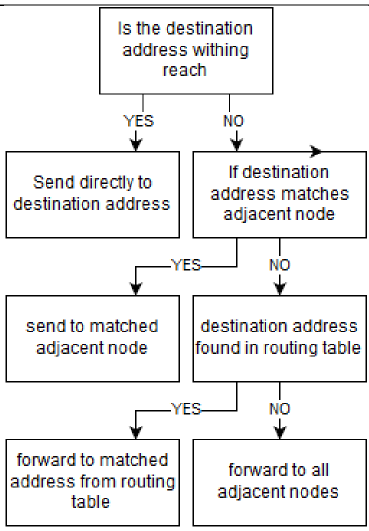

Fig. 8.Flowchart showing how the node forwards the packet by checking the destination address of the network payload.

F. Network Acknowledgement and PID

The acknowledgement is sent in a similar method as a packet is sent. The acknowledgement request is sent in the Packet Info byte of the network structure as seen inTABLE II. . When the receiver receives a packet and the destination matches with that of its own, it keeps the packet and checks if the Packet Info has requested an acknowledgement. Packet disassembly and reassembly must be implemented at higher level by the user. The network layer will allow a maximum of 25 bytes. The disassembly and reassembly of the packet routines are built on top of the network layers using the PID and acknowledgement of the packets. Testing the Network and Results

V. TESTING THE NETWORK AND RESULTS

Testing the effectiveness of the network library has been done and different test scenarios has been created. The tests to be conducted are:

A. Testing the network payload packaging and transmission

This test will make sure the network payload sent from the source to the destination is successfully decoded. The network payload transmission is expected between

```
uint8_t myMesg[25];
sprintf((char*)myMesg, "test");
NRF24L01pNetwork::networkPayload_t myNetPayload;
myNetPayload.srcNodeId = 0x4565;
myNetPayload.destNodeId = 0x5456;
myNetPayload.pid = 0x4d;
myNetPayload.packetInfo = 0x67;
myNetPayload.length = 4;
myNetPayload.payload = myMesg;
Radio.sendToAdjacent(&myNetPayload,
        &Radio.AdjNode[NRF24L01p::PIPE_P1-1]);
```

Fig. 9.Code fragment of the node that transmits the network payload. The payload structure uses the source address 0x4565 and destination address 0x5456. Once the payload packet structure is filled with the informations, the paylaod is sent to adjacent node.

```
65   45   56   54   4d   67   4    74
65   73   74   0    a0   b    d0   76
b8   3e   1    0    0    0    0    0
c8   9    1    0    0    0    0    0

source NodeID : 4565
destination NodeID : 5456
PID : 4d
Packet Info : 67
Length : 4
```

Fig. 10. Terminal of the Receiving node. Once the 32 byte payload is received, it is decoded and the information packed at the transmitting node are unpacked. The bytes in hexadecimal can be seen followed by the network packet informations.

B. Testing the maximum data rate and packet losses against number of hops (PING PONG test)

The nodes and the coordinator are arranged as shown inFig. 11. Once again, for testing, the number of adjacent nodes is limited to 2. This is to ensure that each node can only connect to two adjacent nodes, out of which, one directs towards the coordinator. Node A sends 256 packets to node C, incrementing the PID. When node C receives the payload, it sends a network acknowledgement back to node A, for the corresponding PID of the payload. Node A keeps track of the number of payload it received. The wait time between each payload to be transmitted is varied. A random number within a specified range, determines the time between payload transmission. If the time is short, the number of missed packets will increase and vice versa[12].

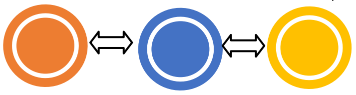

Fig. 11. Arrangement of the nodes where we send network payload from one node to another and measure the maximum speed and lost packets with respect to time and interval between sending the network payloads

Proximity testing (all three nodes are within proximity < 10 m line of sight). The equation used to determine the achievable data rate

$$Datarate = \frac{data\ per\ packet \times (packets\ sent - missed\ PID\ ack)}{total\ time\ in\ ms}$$

Data per packet = 25
Packets sent = 256

TABLE III. RESULT OF ACHIEVABLE DATA RATE OF NETWORK NODES ARRANGED IN CLOSE PROMITY

interval (ms)	90	100	110	120	130	140
Missed Packet / 256	143	60	0	0	0	0
Total Time (ms)	40340	35295	30122	32842	34445	37635
datarate (bytes/sec)	70.03	138.83	212.47	194.87	185.80	170.05

It can be noticed that if the interval between packets sent is less than 110 mS, the number of missed packets increases significantly. This is because the transmitting node must allow the receiving node to process the payload and send back an acknowledgement. This gives us an estimated time of 110 mS that must be given to send a payload and get an acknowledgement back successfully. The data rate that can be achieved is 212.47 bytes per second with a burst interval of 110mS with no missed packets out of the 256 packets.

Testing similarly for nodes placed without line of sight (LOS), with walls single layer wall between each adjacent node, we get,

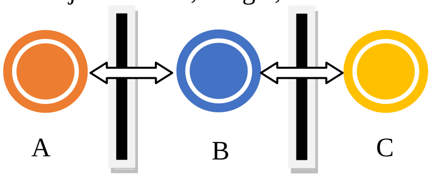

Fig. 12. Arrangement of the nodes where we send network payload from one node to another and measure the maximum speed and lost packets with respect to time and interval between sending the network payloads with introduced sigle layered bricked walls between each adjacent nodes.

TABLE IV. RESULT OF ACHIEVABLE DATA RATE OF NETWORK NODES ARRANGED IN RANGE OF 30 METERS (NO LOS)

interval (ms)	90	100	110	120	130	140
Missed Packet / 256	250	120	6	4	2	0
Total Time (ms)	63212	52124	36654	35514	36625	39542
datarate (bytes/sec)	2.37	65.23	170.51	177.39	173.38	161.85

VI. CONCLUSION

A cluster-tree network solution using the NRF24L01+ low cost low power radio module has been designed which supports up to 65535 nodes, acknowledgement, handling failed node, and packet repeating by each node. The testing has been successful in sending payload over the network from one node to another ensuring single path of the packet transmission. The testing has also shown that a failed node causes a re-routing of the other adjacent nodes to continue having connectivity to the network. The test results demonstrate the packet transmission over certain number of hops over intermittent nodes and the maximum achievable data rate and packet losses. The library for the network class designed by the author is open source and available at the repository [13]

REFERENCES

[1]. J. Leonard, "Not a standard wireles solution," [Online]. Available: https://goo.gl/UAgztR.

[2]. Nordic Semiconductor, "nRF24L01+ Product Specification 1.0," [Online]. Available: https://www.nordicsemi.com/eng/nordic/download_resource/8765/2/39049718/2726.

[3]. Charles, "NRF24L01 real life range test," [Online]. Available: https://hallard.me/nrf24l01-real-life-range-test/.

[4]. J.-S. . Lee, Y.-W. . Su and C.-C. . Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," , 2007. [Online]. Available: http://eee.guc.edu.eg/announcements/comparaitive_wireless_standards.pdf. [Accessed 8 9 2017].

[5]. A. J. V. Abinayaa, "Case Study on Comparision of Wireless Technologies in Industrial Applications," *Internal Journal of Scientific and Research Publications,* vol. 4, no. 2, 2014.

[6]. H. S. A. C. Bhavneet Sidhu, "Emerging Wireless Standards - WiFi, ZigBee and WiMAX," *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering,* vol. 1, no. 1, 2007.

[7]. S. S. Sonavane, B. P. Patil and V. . Kumar, "Experimentation for Packet Loss on MSP430 and nRF24L01 Based Wireless Sensor Network," *arXiv: Networking and Internet Architecture,* vol. , no. , p. , 2010.

[8]. Y. . Liu and X. . Han, "Analysis of the Maximal Transmission Rate Based on NRF24L01 Chip System," , 2010. [Online]. Available: http://ieeexplore.ieee.org/document/5678223. [Accessed 8 9 2017].

[9]. P. . Christ, B. . Neuwinger, F. . Werner and U. . Rückert, "Performance analysis of the nRF24L01 ultra-low-power transceiver in a multi-transmitter and multi-receiver scenario," *Sensors,* vol. , no. , pp. 1205-1208, 2011.

[10]. Nordic Semiconductor, "White Paper : Introduction to wireless networks," [Online]. Available: https://www.nordicsemi.com/eng/nordic/download_resource/8772/3/86861165/1502.

[11]. J. . Sun and X. . Zhang, "Study of ZigBee Wireless Mesh Networks," , 2009. [Online]. Available: http://dl.acm.org/citation.cfm?id=1634285. [Accessed 8 9 2017].

[12]. B. A. Forouzan, Data Communications And Networking, ed., vol. , , : McGraw-Hill, 2007, p. 621–630.

[13]. H. Rahman, "NRF24L01p," [Online]. Available: https://github.com/emoninet2/NRF24L01pNetworking.

[14]. S. A. Alomari and P. . Sumari, "An Overview of Mobile Ad Hoc Networks for the Existing Protocols and Applications," *International Journal on Applications of Graph Theory in Wireless Ad Hoc Networks and Sensor Networks,* vol. 2, no. 1, pp. 87-110, 2010.

[15]. Nordic Semiconductor, "Bluetooth low energy wireless technology backgrounder Version 4 Updated 22 March," [Online]. Available: https://goo.gl/U2A6hx.