# Mobile Cellular Networks and Wireless Sensor Networks: Toward Convergence

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## ABSTRACT

In recent years, machine-to-machine (M2M) communications, which do not need direct interactions from human beings, are booming to meet the fast-increasing requirements of data-centric wireless services and applications. Mobile cellular networks (MCN) and wireless sensor networks (WSN) are evolving from heterogeneous networks to converged networks, in order to support M2M communications. In this article, we investigate and discuss key technical challenges and opportunities for the convergence of MCN and WSN. We propose that the mobile terminals in MCN act as both sensor nodes and gateways for WSN in the converged networks. We evaluated the performance gain, and our simulation results show that better system performance, in terms of throughput, delay, and network lifetime, can be achieved in WSN by using interactive optimization with MCN.


## INTRODUCTION

Machine-to-machine (M2M) communications are emerging as new communication types different from the conventional human-to-human communications [1]. M2M communications are strongly application-oriented, and have been widely used in many areas, such as healthcare and environmental surveillance. As they are highly related to the particular market scenarios and have various optimization targets, different M2M communications may need different technologies. However, generally the terminals in M2M communications have less mobility. Moreover, in certain cases, some terminals can be more powerful by installing multiple Tx/Rx antennas when they are stationary or slowly moving within a fixed area and not limited to size.

M2M communications can be realized separately within various wireless networks, such as mobile cellular networks (MCN), wireless local area networks (WLAN), and wireless sensor networks (WSN). For MCN, the 3GPP is drafting the standards covering machine-type communications for UMTS and LTE systems [2]. Moreover, M2M communications using WLAN as a backhaul have been applied in intelligent residential villages/buildings and automatic assembly lines [3]. The concept of the Internet of Things (IoT) [4], which originated from WSN, is bevoming more popular in China since the middle of 2009. WSNs can be flexibly deployed to support various smart applications. Its key disadvantages include less mobility robustness, small coverage, and weak terminals. In contrast, MCNs have the advantages of mobility robustness, large coverage, and powerful user terminals, but their deployment and management are expensive and complicated. Therefore, it is intuitive to integrate MCN and WSN for supporting M2M communications.

Heterogeneous networks consisting of MCN and WSN appear in many application areas. In China, researchers are keen to combine IoT/WSN with TD-SCDMA technologies to provide M2M communications. For example, China Mobile is leading a national major special project to integrate WSN with TD-SCDMA networks for water resources and quality monitoring applications. In this project, many dedicated mobile phones are equipped with a WSN air-interface for technology testing, evaluation and demonstration purposes. Through the mobile phones, the TD-SCDMA network is integrated with the WSN and provides backhaul data links for the WSN. Meanwhile, the WSN turns into the feelers of the TD-SCDMA network. These mobile phones can collect measurement data from a variety of sensor nodes and then forward this data to an information center of the TD-SCDMA networks. In such a case, MCN is simply used as a backhaul infrastructure for WSN, i.e. there is no dynamic interaction between both networks. We believe joint optimization in heterogeneous networks can effectively improve system performance and thus is the focus of this article.

The convergence of MCN and WSN can benefit both types of network. For WSN, the MCN can enable higher layer control and optimization to prolong network life time, improve WSN system performance, and provide quality of service (QoS) for WSN services. For MCN, WSN can enable the cognitive and intelligent aspects of the cellular system. It is envisaged that the converged network architecture of MCN and WSN could enable better wireless services and more data-centric applications [5]. For example, a MCN can control and manage an attached WSN, thus making WSN more efficient in energy saving and performance


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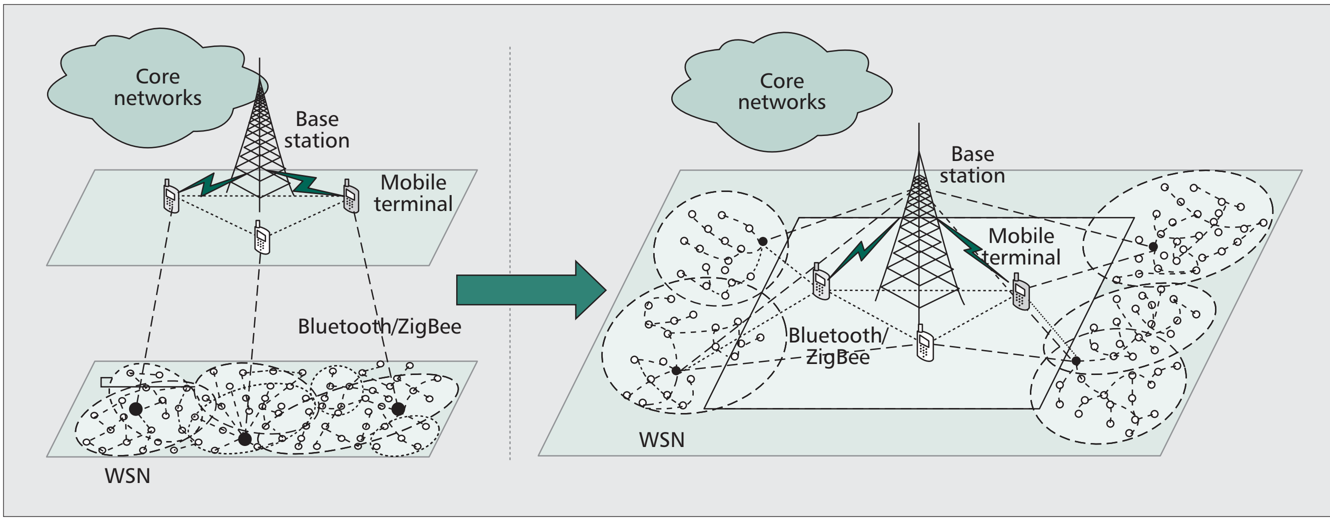


**Figure 1.** *Converged network architecture for MCN and WSN.*

improvement. On the other hand, WSN can enrich mobile applications and provide real-time measurement data for network performance and service coverage optimization in MCN. As for the telemetry and remote management of distributed assets, the convergence of WSN and MCN can be used in the supervisory control and data acquisition system. WSNs in these applications need to be managed and optimized with the aid of MCN. Hence, enabling technologies need to be researched and developed for interactive control and joint optimization of converged MCN and WSN.

In this article, we first provide an overview of the key technical challenges in the evolution process of a converged network architecture of MCN and WSN. A comprehensive technical analysis and discussion of system architectures, air-interface, and network protocols are then given. We also propose that the mobile terminals in MCN act as both sensor nodes and gateways for WSN in the converged networks, and we evaluated the performance gain. Our simulation results show interactive optimization between MCN and WSN in a converged network architecture can effectively improve system performance, in terms of throughput, delay, and network lifetime in WSN.

## Technical Challenges

The future M2M networks should be service-oriented [6]. Various M2M applications are applying to extensive areas such as electricity monitoring, intelligent transportation, automatic industrial control, remote healthcare, water resources and environment monitoring, etc. In the converged MCN and WSN based M2M communications scenarios, a remote sensor gathers data and sends it to a gateway, which is also a mobile terminal of MCN and connected to MCN directly. At this point, the network architecture comes to a layered heterogeneous network, which is an integration of WSN and MCN [5]. To achieve full convergence of MCN and WSN, the following technical challenges need to be overcome.

### Network Architecture Convergence

The conventional network architecture of integrated MCN and WSN is hierarchical, as shown in the left part of Fig. 1. All gateways are dual-mode and have both WSN and MCN interfaces. A group of wireless sensor nodes construct the data detecting plane, while the gateway and base station (BS) comprise the system control plane. WSN is controlled indirectly by the BS through the gateway. The gateway can just provide the access for WSN nodes, and forward the detected data to the backhaul network servers. Communications between WSN and MCN use a data channel at the gateway, which, however, decreases the system efficiency.

In the new network convergence approach, the converged MCN and WSN architecture is evolving from layered to flat to decrease the hierarchical signaling exchanging between the two networks. As shown in the right part of Fig. 1, in the converged architecture the sensor nodes may have the ability to hear the downlink signaling from the BS of MCN. The network architecture becomes flat. As a result, MCN can directly control and manage WSN, thus making WSN more efficient. For example, the BS can help the sensor nodes to choose the optimal transmission path to route the traffic. For the uplink, due to the limited transmission range of sensor nodes, the data is still routed by the gateway. Extra complexity is introduced to the sensor nodes to equip the downlink receiver, but the complexity will not be large since the device capabilities are much higher nowadays.

In the converged architecture, the impact to MCN and the complexity added to the sensor nodes should be evaluated to achieve an acceptable trade-off between the cost and performance gain. The authorization of the sensor nodes at the MCN needs to be studied. The information related to authorization can be relayed by the WSN gateway, which is already authorized in the MCN. Moreover, new time coordination schemes need to be designed for the converged architecture. Since the multi-access scheme in WSN is contention based, while it is scheduling

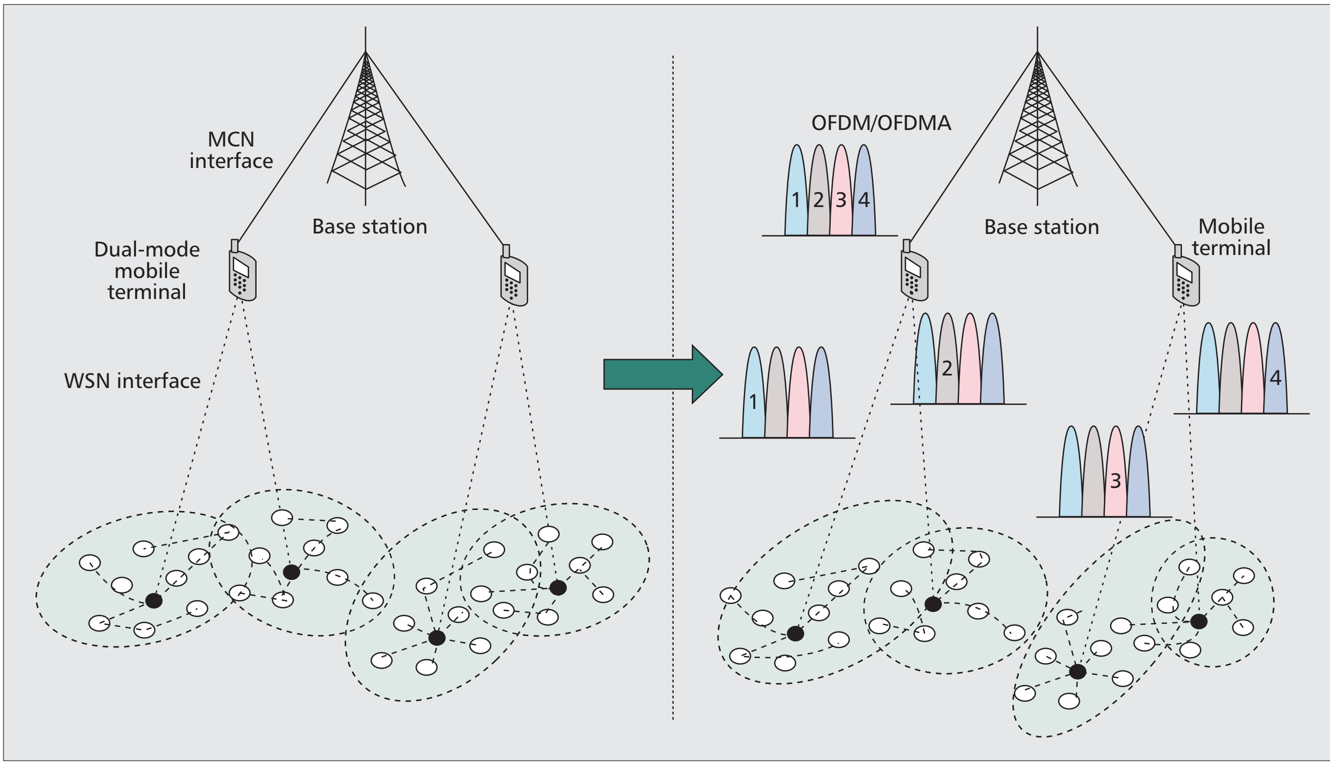


**Figure 2.** *Converged air-interface for MCN and WSN.*

based in MCN, the timing is independent for the two types of network in the converged scenario. Hence, a jointly optimized coordination scheme should be designed to allow the sensor nodes to achieve good tradeoff between energy consumption and the system performance.

### Air-Interface Convergence

Currently, narrowband technologies or spread spectrum transceivers are the main solutions for the air-interfaces of WSN (e.g. Bluetooth and ZigBee), while MCN uses different technologies (e.g. UMTS/LTE/Mobile WiMAX). How to design a converged air-interface for MCN and WSN is a key challenge to gain the mutual benefit from the two types of networks.

The introduction of dual mode mobile terminals is a simple implementation, as shown in the left part of Fig. 2. The main limitation of this solution is that the terminal will frequently switch the mode in order to forward the data from WSN to BS. In MCN, orthogonal frequency-division multiplexing (OFDM) and orthogonal frequency-division multiple access (OFDMA) become the main solution for the air-interface. It has been shown that OFDM/OFDMA is an effective way to share the radio resources between systems with different bandwidth, e.g. the non-continuous OFDM (NC-OFDM) [7] is an OFDM based spectrum pooling technique and has been gaining much attention recently. As the higher data rate applications will be applied to WSN in the future, the OFDM based air-interface comes to an alternative for WSN, and thus, the full convergence of the air-interface becomes possible, e.g. based on NC-OFDM, as shown in the right part of Fig. 2. Each WSN cluster shares a subset of OFDM subcarriers/carriers of the MCN. Within the subset of subcarriers/carriers, the multiple access of sensor nodes is implemented.

However, it is difficult to design a converged air-interface. For example, since the coverage and channel conditions of MCN and WSN are quite different, the cyclic prefix of the two systems should be jointly designed. Besides, the two networks have different signal processing capability, and the bandwidth allocated for the two networks is different, i.e. large bandwidth for MCN while small bandwidth for WSN. If the two networks are working on different frequencies, some adaptive filters should be designed to aggregate a different amount of sub-carriers. Otherwise, if the two networks share the same frequency bandwidth, the converged radio frame needs to be designed to mitigate the multi-access interference between the links from mobile terminals to sensor nodes and the links from mobile terminals to the BS.

## Protocol Convergence

In the converged WSN and MCN scenario, the collected data from the sensor nodes can be routed to the BS by the gateway. Currently, the data channel between the two protocol stacks is usually implemented in the gateway, as shown in the left part of Fig. 3. In this case, data channels between the two independent stacks are implemented to exchange information. Since the network architecture and air-interface are highly converged for WSN and MCN, the protocol and control signaling should also be tightly converged for a real convergence of WSN and MCN. In such a converged network, MAC and network layer protocols in the two stacks should be jointly optimized either to achieve some performance gains for WSN or to extend the applications of MCN. As

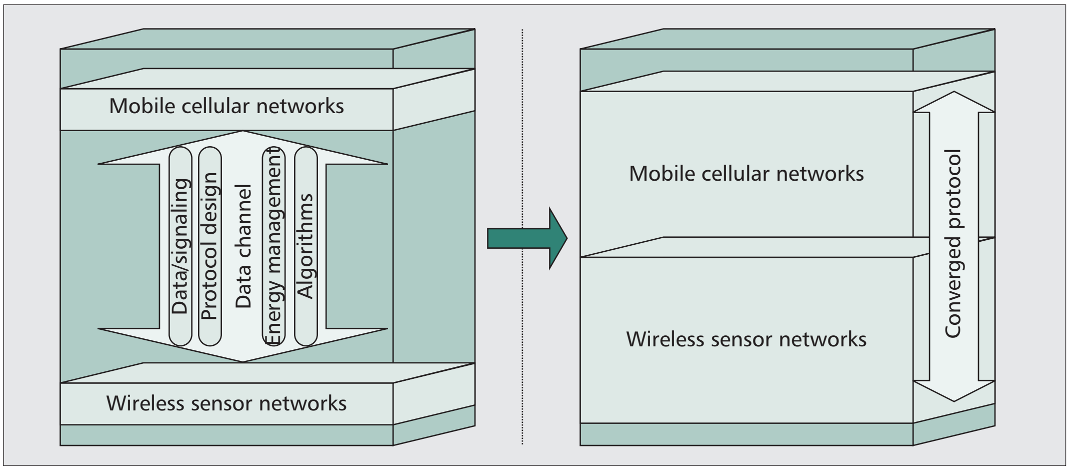


**Figure 3.** *Converged protocol for MCN and WSN.*

*Only one packet is sent when a source node is selected. All the packets arrived at the gateway are considered as effective packets, and the network throughput is calculated from all effective packets.*

shown in right part of Fig. 3, the two protocol stacks are not independent. The data and algorithms are shared between the two stacks.

In the converged networks, the downlink and uplink control signaling should be designed, and some "cross-MAC" designs need to be implemented at the gateway. The new signaling may impact the current WSN and MCN standards. For the downlink, entry/exit of WSN nodes and gateways may be managed by the BS, while for the uplink, the signaling from WSN nodes, e.g. requests for transmitting data, which can be triggered in periodic, on-demand, or event-driven ways, are also coordinated by the BS. Furthermore, in the PHY/MAC layer, the gateway needs to convey the sufficient/efficient control information to and from the BS for convergence optimization. The gateway needs to request the resources from the BS for uplink and downlink transmission, and forward some system information to sensor nodes.

In the MAC layer, a two-level resource allocation scheme should be considered for the converged networks, especially for scenarios where there is large number of WSN nodes with heavy traffic. For example, the gateway can map the data and resource requests of sensor nodes to MCN, and reports to the BS; then the BS allocates a different WSN channel group to each gateway for intra-WSN communications according to the requested information from different gateways.

In the network layer, when a mobile gateway enters the coverage area of WSN, it may cause gateway re-selection or even re-clustering of the wireless sensor nodes. How to achieve a balanced trade-off among complexity, performance gain and energy consumption via robust re-selection and re-clustering algorithms is an essential issue for further study.

## PERFORMANCE EVALUATION

As mentioned in the above sections, both MCN and WSN can benefit from each other in a converged network. However, for MCN the benefit brought from WSN is mainly in extending applications. The key performance metrics of MCN will remain unchanged, except for introducing some signaling overhead. Comparably, with the help of MCN, the performance of WSN can be improved, e.g. with mobile terminals as redundant gateways, data can be transmitted to core networks more efficiently. As a result, here we only evaluate the performance of WSN in converged scenarios. It should be clarified that the technology challenges discussed in a previous section are not evaluated in this section, because the detailed technologies need further study, and they will be our future work.

### EVALUATION SETUP

The performance of the converged MCN and WSN was evaluated by extensive computer simulations and compared with the ordinary sole WSN scenario. To investigate the impact of network size on performance, two networks of 50 and 100 sensor nodes, respectively, are considered in the simulation. In both cases, the nodes were randomly distributed in the same $100 \times 100$ m$^2$ square field, i.e. the $x$ and $y$ coordinates of a sensor node are independently and uniformly distributed in (0, 100). The default gateway of WSN was located at the position of ($x$ = 0 m, $y$ = 0 m). All the normal nodes have the same initial energy of 1 Joule and have the capability of adjusting their transmission power to minimize interference and ensure error-free packet transmissions. In the converged network, a number of sensor nodes were randomly chosen as enhanced mobile terminals (defined as gateway MT), which have the ability to be WSN gateways in addition to their basic function as sensor nodes, i.e. they can transmit their data to the Internet directly, and each gateway MT has initial energy of 10 Joule.

In our simulation, each sensor node has one packet at the beginning of a transmission round. The source node that sends a packet is randomly chosen among all sensor nodes who have more than one packet and whose remaining energy is larger than zero. Only one packet is sent when a source node is selected. All the packets arrived at the gateway are considered as effective packets, and the network throughput is calculated from all effective packets. Data packets are of the constant size of 2000 bits, and the first-order radio model [8] was used to calculate the energy consumption for receiving and transmitting a packet. In the first-order radio model, a sensor node consumes $E_{Rx}(k) = \xi_{elec} \cdot k$ Joule of energy for receiving a $k$-

bit packet, while for transmitting a $k$-bit packet to another node over a distance of $d$ meters, the energy consumption is $E_{Tx}(k, d) = \xi_{elec} \cdot k + \xi_{amp} \cdot k \cdot d^2$. In our simulation, we set $\xi_{elec} = 50nJ/bit$, and $\xi_{amp} = 100pJ/bit/m^2$ [8, 9]. In addition, nearest routing is used in our simulation, i.e. a sensor node will transmit its packet to the gateway if the gateway is within its transmission range, or else it will choose its nearest neighbor to route the packet for low energy cost. No concurrent transmission is allowed in our simulation.

## Numerical Results

Figures 4 and 5 show the network lifetime with different scenarios as a function of the number of died nodes. For generality and accuracy, all the simulation results are the average of 30 similar simulations for different random seeds. As shown in Figs. 1 and 2, when the amount of gateway MTs increases, the lifetime of the network extends. Since the initial energy of gateway MTs are larger than ordinary sensor nodes, we also simulated the scenario that the initial energy of five randomly chosen sensor nodes are set to 10 Joule while there are no gateway MTs (called energy boosts in the figures). In this scenario, the lifetime for the last node dies is much larger than others, because the nodes with larger energy live for the longer lifetime compared to the gateway MTs with the same energy. The gateway MT needs to route other nodes' packets to the Internet, so its lifetime is not as long as the normal nodes with the same energy. However, in practical scenarios, when most nodes of WSN have died, the network may not work properly. The authors in [10] suggest that the lifetime of WSN should be defined as the time when there is a cut-set of sensor nodes in the network occurs. In our simulation, we take the lifetime of half nodes dies for comparison, the converged network with three gateway MTs has equal or better performance than the energy boost case, which is with five energy boosted sensor nodes.

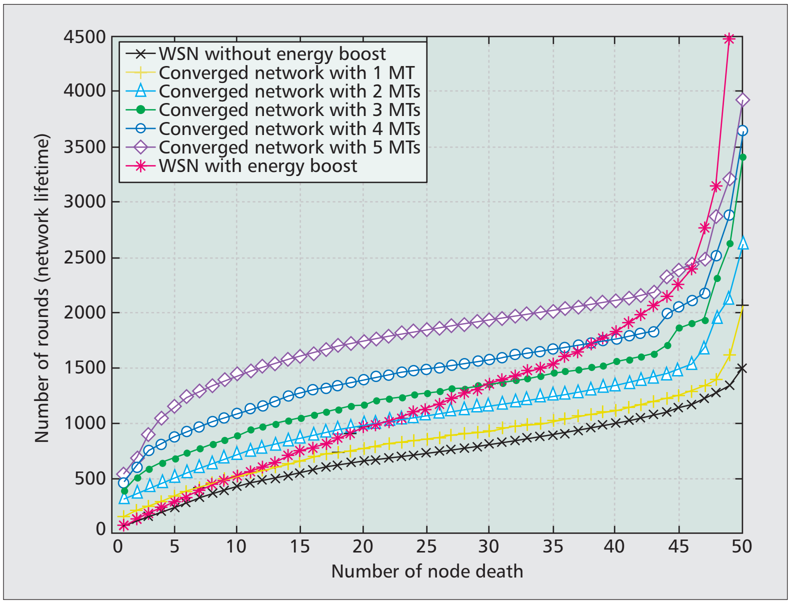


**Figure 4.** *Network lifetime for a network with 50 sensor nodes.*

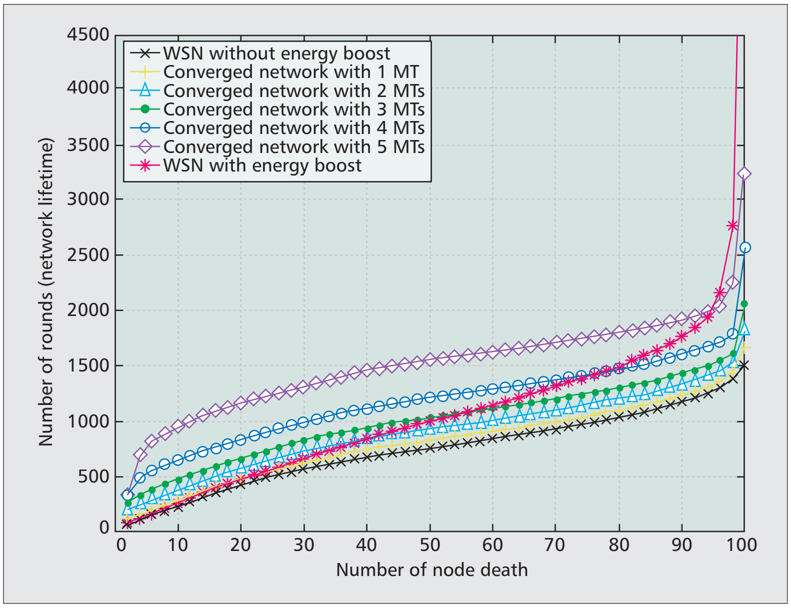


**Figure 5.** *Network lifetime for a network with 100 sensor nodes.*

The main results against different performance metrics are summarized in Table 1. Similar to the network lifetime, the performance of average energy consumption and throughput have the same trends when the evaluation scenario changes, because the throughput is mainly related to the speed of nodes dying. We only collect the throughput and delay data for the first 500 rounds, in which only a small portion of nodes have died. As a result, comparing the throughput of CN with WSN W/EB, the improvement is not that significant. Since there are multiple gateways in the converged network, the average delay of the converged network is smaller than that of the conventional WSN, and the delay is further reduced when the number of gateway MTs increases.

It is seen from the obtained results for different network sizes that the denser network of 100 nodes has more resources (e.g. energy and nodes) and also more traffic. Though the average communication distances between the nodes are shorter, the energy consumption per round in the 100-node network increases about 75–90 percent, while the throughput increases about 70–85 percent, compared with 50-node network. Moreover, the impact a gateway MT can bring is not as much as that for the 50-node scenario. As shown in Fig. 5, the network lifetime obviously increased when there are four gateway MTs in the denser network, while only two gateway MTs can bring the same effect in the 50-node network. However, if the concurrent transmission is used, and some more effective routing algorithm is implemented, the energy consumption per packet can be reduced in denser network [8], as the gateway MTs can play more important roles.

## Conclusions

MCN and WSN are evolving from heterogeneous to converged, in order to meet the increasing requirement for M2M communications. Although there are many technical challenges in the converged process, such as new network architecture, air-interface, and protocols, the convergence will

| Performance metrics | | (a) A network of 50 sensor nodes | | | | | (b) A network of 100 sensor nodes | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WSN w/o EB | WSN w/ EB | CN w/ 1 MT | CN w/ 3 MTs | CN w/ 5 MTs | WSN w/o EB | WSN w/ EB | CN w/ 1 MT | CN w/ 3 MTs | CN w/ 5 MTs |
| Network Lifetime (rounds) | FND | 76.0 | 76.6 | 147.1 | 392.4 | 533.3 | 43.7 | 46.7 | 80.0 | 190.9 | 254.3 |
| | HND | 726.5 | 1125.4 | 854.2 | 1272.3 | 1842.2 | 750.5 | 996.1 | 818.4 | 1031.1 | 1548.1 |
| | LND | 1502.8 | 9392.6 | 2060.4 | 3414.0 | 3921.9 | 1517.1 | 7300.8 | 1658.5 | 2066.3 | 3221.1 |
| Energy Consumption ($*10^{-3}$ J/round) | | 56.8 | 54.1 | 54.9 | 52.3 | 46.5 | 98.9 | 98.2 | 97.3 | 92.4 | 89.2 |
| Delay (slots/round) | | 51.5 | 28.0 | 21.4 | 13.8 | 11.1 | 103.0 | 61.4 | 49.6 | 31.2 | 28.6 |
| Throughput (packets/round) | | 42.3 | 45.3 | 43.2 | 45.7 | 46.7 | 71.3 | 83.2 | 73.9 | 83.9 | 86.4 |

**Table 1.** *Performance comparison of different scenarios (FND: first node dies, HND: half node dies, LND: last node dies, EB: energy boost, CN: converged networks.)*

bring about notable advantages. By computer simulation, we showed that the average delay, throughput, and life time performance of WSN can be remarkably increased in a converged network.

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## References

[1] J. Brazell *et al.*, M2M: The Wireless Revolution, TSTC Publishing, ISBN: 0-9768503-4-6, June 2005.

[2] Huawei, "Status Report for SI on RAN Improvement for Machine-Type Communications," RP-100500, 3GPP TSG RAN #48, Seoul, June 2010.

[3] D. Bansal, J. Bao, and W. Lee, "QoS-Enabled Residential Gateway Architecture," *IEEE Commun. Mag.*, vol. 41, no. 4, Apr. 2003, pp. 83–89.

[4] ITU Internet Reports 2005: The Internet of Things, Nov. 2005, http://www.itu.int/osg/spu/publications/internetofthings/, last accessed: Sept. 28, 2010.

[5] F. Hu and S. Kumar, "The Integration of Ad Hoc Sensor and Cellular Networks for Multi-Class Data Transmission," *Ad Hoc Networks*, vol. 4, no. 2, Mar. 2006, pp. 254–82.

[6] Y. Qian *et al.*, "Service-Oriented Broadband Wireless Network Architecture," *IEEE Wireless Commun.*, vol. 16, no. 4, Aug. 2009, pp. 14–15.

[7] R. Rajbanshi, A. Wyglinski, and G. Minden, "An Efficient Implementation of NC-OFDM Transceivers for Cognitive Radios," *Proc. 1st Int'l. Conf. Cognitive Radio Oriented Wireless Networks and Commun.*, Mykonos Island, June 2006, pp. 1–5.

[8] Y. Yang, H-H. Wu, and H-H. Chen, "SHORT: Shortest Hop Routing Tree for Wireless Sensor Networks," *Int'l. J. Sensor Networks*, vol. 2, no. 5/6, July 2007, pp. 368–74.

[9] S. Lindsey, C. Raghavendra, and K. M. Sivalingam, "Data Gathering Algorithms in Sensor Networks Using Energy Metrics," *IEEE Trans. Parallel and Distributed Systems*, vol. 13, no. 9, Sept. 2002, pp. 924–35.

[10] O. Chipara *et al.*, "Real-Time Power-Aware Routing in Sensor Networks," *Proc. 14th IEEE Int'l. Wksp. Quality of Service (IWQoS '06)*, New Haven, Conn, USA, June 2006, pp. 83–92.

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