

# Cross-Layer Cooperative Scheduling Scheme for Multi-channel Hybrid Ubiquitous Sensor Networks

Yingji Zhong, Qinghai Yang, Kyung Sup Kwak, and Dongfeng Yuan

**The multi-scenario topology of multi-channel hybrid ubiquitous sensor networks (USNs) is studied and a novel link auto-diversity cross-layer cooperative scheduling scheme is proposed in this paper. The proposed scheme integrates the attributes of the new performance evaluation link auto-diversity air-time metric and the topology space in the given multi-scenario. The proposed scheme is compared with other schemes, and its superiority is demonstrated through simulations. The simulation results show that relative energy consumption, link reception probability, and end-to-end blocking probability are improved. The addressing ratio of success with unchanged parameters and external information can be increased. The network can tolerate more hops to support reliable transportation when the proposed scheme is implemented. Moreover, the scheme can make the network stable. Therefore, the proposed scheme can enhance the average rate performance of the hybrid USN and stabilize the outage probability.**

**Keywords:** Cross-layer, cooperative scheduling, multi-channel, hybrid USN.

## I. Introduction

Wireless sensor networks [1] have drawn the attention of the research community in the last few years, driven by a wealth of theoretical and practical challenges. The growing interest can be largely attributed to the new applications enabled by the large-scale networks of small devices capable of harvesting information from the physical environment, which perform simple processing on the extracted data and transmit it to remote locations. Significant results in this area over the last few years have ushered in a surge of civil and military applications. As of today, most deployed wireless sensor networks measure scalar physical phenomena like temperature, pressure, humidity, or location of objects. In general, most of the applications have low bandwidth demands, and are usually delay tolerant.

Ubiquitous sensor networks (USNs) [1] have made major strides over the past years and are rapidly proving to be a leading solution. The low cost and quality of service (QoS) assurance provided by USNs make them commercially viable to support further applications, as they can fuse data originating from heterogeneous sources. Many applications require the sensor network paradigm to be rethought, taking into consideration the need for mechanisms to deliver data with a certain level of QoS. However, to provide diverse services over USNs, many challenging issues need to be addressed. We need to clearly understand the wireless link budget, the wireless channel characteristics, and the packet error rate. The relationship between the packet error rate and the effective frame rate must be considered. The solution will be enabled by the convergence of communication and computation with signal processing and several branches of control theory and embedded computing. This cross-disciplinary research will

---

Manuscript received Jan. 31, 2008; revised June 18, 2008; accepted Aug. 20, 2008.

Yingji Zhong (phone: +82 32 860 9189, email: zhongyingji32@sdu.edu.cn) and Kyung Sup Kwak (email: kskwak@inha.ac.kr) are with UWB-ITRC, Inha University, Incheon, Rep. of Korea.

Qinghai Yang (email: yangqing-hai@hotmail.com) is with Xidian University, Shaanxi, China.

Dongfeng Yuan (email: dfyuan@sdu.edu.cn) is with the School of Information Science and Engineering, Shandong University, Shandong, China.

enable distributed systems of heterogeneous embedded sensor devices to interact and control the physical environment.

Hybrid sensor networks [1], [2] provide novel infrastructures which combine cellular networks with self-organizing mechanisms. Cooperative scheduling has recently attracted much attention because it realizes a frequency sharing system at the frequency band assigned to the primary system. In the cooperative process, the secondary cooperative terminals transmit signals on the frequency band assigned to the primary system by sensing the radio frequency band, thus avoiding interference with the primary systems. However, it is difficult to recognize the status of the frequency band when only the primary terminals receive the signals. Therefore, the use of sensor cooperative scheduling to realize a wide area secondary communication system using multi-hop networks is necessary. Topology space analysis in a special scenario can be useful in designing the proposed scheme to effectively utilize location marking information and to address the performance issues. Although the high transmission power on single-hop networks can support a large communication area, interference with the primary system also increases if the primary system is between the primary transmitter and the receiver. In sensor cooperation, the power of each node is suppressed to minimize the interference with the primary system and the area of communication can be expanded by the use of multi-hop networks. However, the scheduling framework is complicated because the location and the active time of the primary system are not fixed. The hybrid USN has the potential to enable a large class of applications ranging from assisting the elderly in public spaces to border protection, which can benefit from the use of the numerous sensor nodes for delivering packets. In multi-hop wireless networks, there is a strictly interdependent cross-layer coupling of functions handled at all layers of the communication stack. Multiple paths may exist between a given source-sink pair, and the order of packet delivery is strongly influenced by the characteristics of the route chosen. As an additional challenge, in real-time feeds or streaming media, information that cannot be used in the proper sequence becomes redundant, thus increasing the need for transport layer packet reordering. Functionalities handled at different layers are inherently and strictly coupled due to the shared nature of the wireless communication channel. Hence, the various functionalities aimed at QoS provisioning should not be treated separately when efficient solutions are sought. Multiple routes may be necessary to satisfy the desired data rate at the destination node. There are efficient differentiations between flows with different delay and reliability requirements.

To improve the robustness of the sensor cooperation without a complicated scheduling framework, we propose a performance evaluation metric and a cross-layer cooperative

scheduling scheme for ZigBee-based multi-channel hybrid USNs. We address the existing questions and attempt to design a viable end-to-end solution. We also identify the key design parameters and present a methodology to optimize cross-layer efficiency, data quality, and coverage area. To the best of our knowledge, such a study was not thoroughly conducted in [3] and [4].

To this end, the scheme we propose can support packet-based delay guarantees that must be delivered with a given probability. In this case, cooperative communication considerably improves the network connectivity. The proposed metric is a measure of the probability that a packet will reach its destination within the required delay bounds. It is based on a cross-layer approach between the network and the MAC layers in which a judicious choice is made between the reliability and timeliness of the packet arrival. We argue that differentiation of reliability is an effective way of channeling resources from flows with relaxed requirements to flows with tighter requirements. To describe the system implementation of the proposed scheme, we also propose a novel cross-layer communication architecture. The proposed architecture provides modified wireless link abstractions and suggests tradeoff in complexity at the physical and higher layers.

The rest of the paper is organized as follows. In section II, we present the evaluation architecture and perform dimensional analysis for the topology in a special scenario. In section III, we propose a performance evaluation metric, the cross-layer cooperative scheduling scheme, and the cross-layer communication architecture. In section IV, we evaluate the performance of the proposed scheme and analyze the improvement of the cooperative scheduling guarantee via simulation. Finally, we conclude in section V.

## II. Evaluation Architecture and Dimensional Analysis

### 1. Channel Model

In randomized cooperation, each node projects the rows of the state matrix that can generate a randomized state,  $\tilde{x}_r = Xr_r = H_{M \times N}(s)r_r$ , where  $H_{M \times N}(s)$  is the prospective state matrix with  $M$  rows and  $N$  columns, and  $r_r$  represents the contra-variant vector [5] of the temporary state. The received vector is a mixture of these randomized states convolved with their respective channel impulse response, as shown in (1).

$$y_i = \sum_{i=1}^N M_{ir} \tilde{x} + \delta_i, \quad (1)$$

where  $M_i, i = 1, \dots, N$ , are the equivalent convolution matrices, and  $\delta_i$  is the  $i$ -th offset vector which is equivalent to

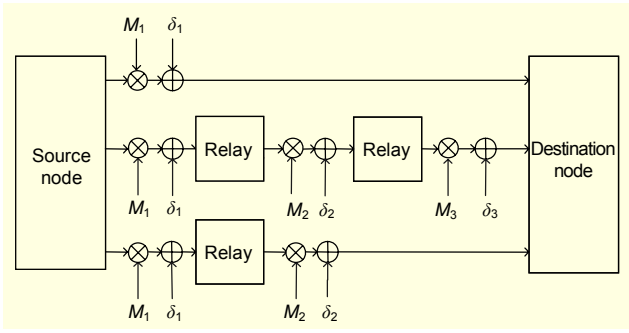


Fig. 1. Channel model.

the cooperative state. The diversity that can be obtained through this scheme depends on the statistics of the resulting equivalent states and on the particular selection of the state just as it does for the deterministic assignment. For simplicity, we consider a scenario in which the channels between the source node and the destination node are orthogonal and  $i=1, 2, 3$ . A message that contains a request for cooperation is stored in the relay buffer, whose transmission is synchronized by the preamble sequence received in the message. The state parameters in the network layer need to be informed about the state of the relay buffer. In general, the half-duplex constraint of the channel model mandates that the destination node be inactive when the source node is busy, but the upper layer can also prevent cooperative transmission for it, as shown in Fig. 1. In this form of cooperation, several radios collaborate to realize an antenna array, thereby leveraging the processing gains of an antenna array without each subscriber unit needing to have its own antenna array. A number of radios can cooperate to transmit or receive the same signal, thereby realizing transmit or receive diversity functions. The normal processes of cooperation may be able to provide the information necessary or perhaps this information could be collaboratively collected into some environmental map.

To avoid cycles, the selection rule should exclude from the iteration of set  $S[m]$  at the  $m$ -th iteration of all points that have been in previous sets  $(x_j, y_j) \in S[i], i=1, 2, 3$ . Using the same definition of connectivity, the state is mapped to a receiving message in the  $m$ -th iteration if the receiver  $SNR_m(x_j, y_j) > \tau$ . The broadcast scheme could use all such states to cooperate, and the set  $S[m]$  is

$$S[m] = \{(x_j, y_j) : (SNR_m(x_j, y_j) > \tau) \cap \Theta\},$$

$$\Theta = (x_j, y_j) \notin \bigcap_{i=1}^3 S[i], \quad (2)$$

where the additional condition  $\Theta$  verifies that the node has not transmitted before. As in the case with only amplify-and-forward, the resultant composite signal at the relay is

$$\tilde{y} = \begin{bmatrix} M_1 \\ \beta M_2 \end{bmatrix} x + \begin{bmatrix} m_1 \\ m_2 \end{bmatrix}, \quad (3)$$

where  $\beta = \left( \sqrt{\frac{P_t/2}{M_2 \sum_x M_2^T}} \right) / \left( 1 + \sqrt{\frac{P_t/2}{M_2 \sum_x M_2^T + 1}} \right)$ , and  $m_1$

and  $m_2$  represent the delay correction facts before and after separate relaying. For fixed  $\beta$ , the sum rate achievable of  $P_t$  from the cooperative transmitter to the receiver is equal to the sum capacity of the dual multiple-access channel. The sum capacity must be characterized in terms of maximization as

$$R^{coop} = \max_{T, (Q_1+Q_2) \leq P_t} \log \left| I + \tilde{M}_1^T d Q_1 \tilde{M}_1 + \tilde{M}_2^T Q_2 \tilde{M}_2 \right|, \quad (4)$$

where the maximization is over covariance matrices  $Q_1$  and  $Q_2$  with  $\tilde{M}_1 \triangleq \begin{bmatrix} M_1 \\ \beta M_2 \end{bmatrix}$ , and  $\tilde{M}_2 \triangleq \begin{bmatrix} \beta M_1 \\ M_2 \end{bmatrix}$ . For fixed  $P_t$ , the achievable minimum rate is  $\min(2R_t, R^{coop})$ . The relays are used to exchange control messages and assign the dedicated channel. In high bandwidth applications, the use of a separate channel for channel arbitration alone does not allow the best utilization of the network resources. It is necessary to directly maximize the achievable rates over all choices of  $R_t$ , where the same channel is used for both data and channel arbitration. The scaling term  $\beta$  can be made close to one. Thus, the composite channel capacity is equal to the point-to-point MIMO capacity of the original channel [5]. Such a model can undoubtedly improve bandwidth efficiency and introduce the problem of distinct channel assignment and the need to account for the delay switching to a different channel as its cumulative nature at each hop affects flows.

## 2. Evaluation Architecture

Figure 2 shows the multiple cell environment of our evaluation model with seven cells in which the nodes are in point-wise uniformity.

Our single-scenario hybrid USN is based on a two-dimensional structure, that is to say, the nodes and the base stations belong to a dual-ring topology. The network topology used in this scenario consists of concentric circles, represented by  $C_k, k \in [1, 2]$ , and the base station of cell 1 is situated at the center of  $C_1$ . For simplicity, we assume that the interference range of each node is almost equal to its transmission range in this specific scenario. All the links are free of transmission error, and the raw capacity of each link is 250 kbps. A node chooses multi-hop transmission through its neighbors with the help of the fixed selection criterion rather than accessing the base stations directly. Since scheduling is used at the base stations, it is possible to assign different carrier frequencies to the different

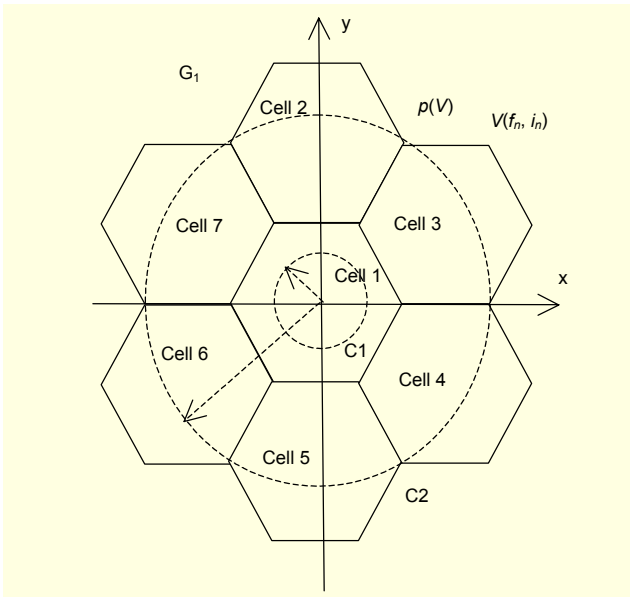


Fig. 2. Dual-ring topology single-scenario with multiple cells.

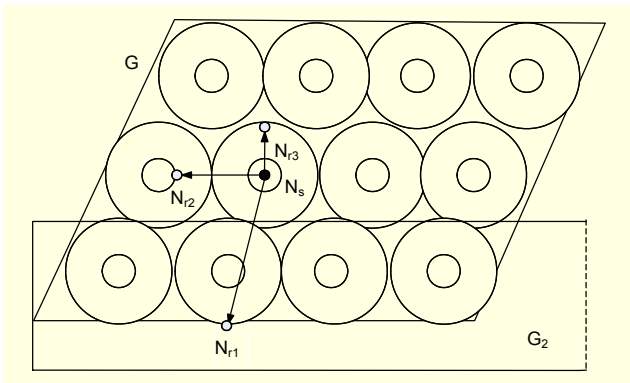


Fig. 3. Dual-ring topology multi-scenario architecture.

multi-hop routes. With the help of the single-scenario structure, the multi-scenario can be induced. Figure 3 shows the optimal cell tessellation. We consider the cooperative diversity based on multi-hop transmission throughout the network using the centers of the cells and compare the total powers' expenditure. Each node makes decisions independently in this hybrid network and causes inconsistency when two nearby nodes adjust their topology simultaneously. Thus, both channel adjustment and power adjustment must guarantee the exclusivity of the cross-layer adjustment in the interference area of the node. Under this premise, each node may locally make adjustment decisions without considering the disturbance of neighboring nodes. The multi-channel hybrid USN we considered is denoted by  $G=(V, E)$  where  $V$  is the set of nodes and  $E$  is the set of links. Let  $G_1=(V, E)$  represent the graph deduced by the single-scenario structure, and  $G_2=(V, E')$  represent the graph deduced by the channel assignment

scheme, where  $G_1 \subseteq G_2 \subseteq G$ . If the network is set to meet the same  $SNR_m(x_j, y_j)$  threshold constraints, each node has to transmit  $P_t \geq \tau P^{coop}$ . Thus,  $P^{non-coop} = N_s N_r P^{coop}$  and the percentage gain of  $P^{coop}$  versus  $P^{non-coop}$  approaches 40%, where  $N_s$  and  $N_r$  represent the transmission probabilities of the source node and the relay module, respectively. As shown in Fig. 3,  $N_{r1}$ ,  $N_{r2}$ , and  $N_{r3}$  can also be considered the transmission probabilities of the three neighboring nodes to be chosen as the relay nodes.

### 3. Dimensional Analysis

Let  $F = C_1 \cup C_2$ , and  $C_1$  is the compact subset of  $F$ . The open covering  $U$  is composed of the neighborhood basis of  $E$ , and the finite subset  $U'$  of  $U$  can cover  $C_1$ . Then  $F \cup U'$  is the finite set, and  $U$  has finite sub-covering. The disjoint uncountable open set family of  $F$  is  $\{\{f\} : f \in C_2\}$ , so that  $F$  is not a metrical compact space. Let  $K_1 \neq \emptyset$ . Then, if  $p$  has a countable basis in the compact metric space,  $\{F_n\} \in G_1$  is the finite covering of  $K_1$ . We have  $F_n = \{V(f_n, i_n) : i_n \leq K_n\}$  for each  $n \in G_2$  and subset  $K_n \subset G_1$ , where  $V(f_n, i_n)$  is an open arc at the center of  $C_2$ . Let

$$U_n = \left( \bigcup_{i_n \leq K_n} V(f_n, i_n) \cup pV(f_n, i_n) / \{f_n, i_n\} \right) \cup G_2, \quad (5)$$

and  $T$  is the family of all the open sets of  $(S, D_m)$ . The comments precede this proposition state  $S$ , and  $D_m$  is the dimensional factor of  $G_2$ . Suppose  $U$  and  $V$  are open sets, and  $p \in U \cap V$ . Then, there exist positive real numbers  $r$  and  $s$  such that  $U \supset N_r(p)$  and  $V \supset N_s(p)$ . If  $t$  denotes the closed set element, then,  $U \cap V \supset N_t(p)$ . Thus,  $U \cap V$  is also the open set. If  $\gamma_{sa} = \{U_\alpha | \alpha \in G_1\}$  and  $\gamma_{sr} = \{U_\beta | \beta \in G_2\}$  are the families of the open sets, then  $U$  is the union of  $U_\beta$ . There exists an index  $\beta_0$  such that  $p \in U_{\beta_0}$  and

$$U \supset U_{\beta_0} \supset N_r(p). \quad (6)$$

It follows that if  $U$  is open, each  $U_n$  is the open set of  $F$  and  $K_n \subset U_n$ . For each neighborhood of  $K$  in  $F$ , if  $f \in K_n$ , there should be an arc  $V(f)$  of  $C_2$ , which has its center at  $f$  and  $V(f) \cup p(V(f) / \{f\}) \subset U$ . Due to the compactification of  $K$ , we have  $K_n \subseteq U_n \subseteq U$ , and each compact subset has a countable neighborhood basis in  $F$ . Therefore, the open sets  $(S, D_m)$  of a metric space constitute a topology on  $S$ , and the dual ring topology belongs to the Alexandroff dual ring space [6]. The attributes of this space are potentially useful for the proposed cooperative scheduling scheme. However, a distinct difference in this case is that the nodes themselves can also function as active nodes. These nodes under group-oriented operation are capable of initiating communications not only with themselves, but also with others.

This analysis demonstrates that only considering channel assignment and routing is not sufficient in hybrid USNs. To fully reduce co-channel interference and consequently achieve better network performance, topology attributes and cooperative scheduling should be jointly considered to exploit both channel diversity and spatial reusability.

### III. Performance Evaluation Metric, Cross-Layer Cooperative Scheduling Scheme, and Cross-Layer Architecture

#### 1. Performance Evaluation Metric

The physical layer sub-problem addresses the transmission interference among nearby nodes and provides the upper layers with a convex set of capacity graphs supported by a finite set or the basis of elementary capacity graphs. That is, finding the ensemble of flows in all the links which attain the maximum total flow is *NP*-complete. Inspired by the work of Saraydar [7], we use a tax mechanism and assume each link player maximizes its own payoff function as

$$\max_{q_l} Q_l^{PHY} = \mu_l \log\left(1 + \frac{G_l q_l}{\sum_{j \neq l} G_j q_j + \sigma_l^2}\right) - t_l q_l, \quad (7)$$

$$0 \leq q_l \leq q_{l,\max} \quad \forall l,$$

where  $t_l$  is the tax rate of link  $l$ ,  $q_l$  is the temporary action of link  $l$ ,  $\mu_l$  is the temporary load of link  $l$ ,  $G_l$  is the temporary gain of the intra-links, and  $G_j$  is the temporary gain of the inter-links. The more power link  $l$  uses, the more interference is produced to flows. In general, not every game has the Nash equilibrium, so we propose a new performance evaluation metric to ensure that a game converges for the stable Nash equilibrium and the cooperative scheduling.

In an action profile, if the result is that each user's action is the best response to the others, the Nash equilibrium is reached [8]. In other words, the Nash equilibrium is the action profile  $(p_r^*, m^*, p^{coop}, n^*)$  where no user has an incentive to deviate by choosing another action, given that the other user's action is fixed. Formally, the Nash equilibrium can be acquired by the following action profiles for each node of the networks:

$$(p_r^*, m^*) = \arg \max U_r^{mh}(p_r, m)$$

$$\text{s.t. } 0 \leq p_r \leq p_r^{\max}, m \in (0, 1), mf(\gamma_{sa}) \leq n^* f(\gamma_{sr}^*),$$

$$(p^{coop}, n^*) = \arg \max U_s^{mh}(p^{coop}, n)$$

$$\text{s.t. } 0 \leq p^{coop} \leq p^{coop\max}, n \in (0, 1), nf(\gamma_{sr}) \leq m^* f(\gamma_{sa}^*),$$

$$(8)$$

where  $U_r^{mh}$  and  $U_s^{mh}$  are the unions of the  $G_1$  and  $G_2$ , respectively.

For multi-hop transmission, the equilibrium action profile must satisfy the opposing throughput constraints of the maximization problems. This opposing throughput constraint is  $p_r^* f(\gamma_{sr}^*) = p^{coop} f(\gamma_{sa}^*)$ . Clearly, the non-forwarding action profile  $(p_r^*, 0, p^{coop}, 0)$  in (8) satisfies the above constraint and always exists in the game.

Generally speaking, both the transmit diversity and the spatial reusability affect the network performance in hybrid USNs. Wu [9] has given the *equivalent channel air time metric* (ECATM) to reflect the spatial reusability characteristic. For hybrid USNs, it resides between the MAC and network layers. Its purpose is to improve the network performance by coordinating the transmission power. Channel assignment and route selection among multiple nodes are distributed. Based on the preceding analysis, we propose the new performance evaluation metric called *link auto-diversity air-time metric* (LADATM), which is defined as

$$\text{LADATM}_i = \sum_c \sum_l r_l^c RT_l^c U_l^c \mu_l Q_l W(i) / CF^c, \quad (9)$$

where  $c$  is the available channel,  $l$  is the co-channel link that lies in the interference range of a specific node,  $r_l^c$  is the number of available links for channel  $c$ ,  $RT_l^c$  is the round trip factor of the corresponding channel,  $U_l^c$  is the iterative update of the state,  $Q_l$  is the quality of the link,  $W(i)$  is the factor of the scheduling priority,  $CF^c$  is the channel reuse factor on channel  $c$ , and  $\text{LADATM}_i$  is the aggregated link diversity air time for potential candidates. It acts as an indicator for the network performance.

#### 2. Cross-Layer Cooperative Scheduling Scheme

The primary purpose of our scheme is accomplished at the cost of latency and by allowing throughput degradation. A sophisticated duty cycle calculation based on permissible end-to-end delay needs to be implemented. The coordination of overlapping listen periods among neighbors based on this calculation is a difficult research challenge. When the end-to-end traffic is split in the multi/dual ring topology, the number of routes between the source and destination should be more than one. That is to say, the flow going through the route is no longer an integer and the traffic demands can be split [10]. The relative bandwidth constraints can be written as

$$\sum_j \sum_{(t,d)} y_{jk}^{td} + \sum_j \sum_{(t,d)} y_{kj}^{td} \leq B, \quad \forall j, k, t, d \in N, \quad (10)$$

where  $y_{jk}^{td}$  is the amount of traffic of node pair  $(t, d)$  that goes through link  $(j, k)$ ;  $y_{kj}^{td}$  is the amount of traffic of node pair  $(t, d)$  that goes through link  $(k, j)$ ;  $B$  is the maximal bandwidth; and

$$y_{jk}^{td} \geq 0, y_{kj}^{td} \geq 0, \forall j, k, t, d \in N.$$

The interference constraints can be written as

$$I(e) = \sum_l Load(I_l), \quad (11)$$

where  $I(e)$  experienced by the link  $e \in E$  is the sum of the traffic load on all the interfering links, and  $I_l$  denotes the interfering link.

The process of the proposed LAD-CCSS is shown in procedure 1.

#### Procedure 1. LAD-CCSS

```

Init() {
  maximize  $U_s^{mh}(p^{coop}, n)$  without constraints;
  maximize  $U_r^{mh}(p_i, m)$ ;
  for each available channel  $c \in \{c_1, c_2, \dots, c_L\}$ 
  if  $t=0$ 
     $J_{prio} = Prand(i)W(i)$ ;
  else
     $J_{prio} = Prand(i)W(i)CF^c$ ;
  end if
  analyze the contention of links on channel  $c$  in two hop range;
  if  $i$  is bound to nodes of neighboring cluster
    then assign  $i$  and make the channel assignment from its neighbor assignment;
  else
    set  $y_{ij}^{td} = y_{ji}^{td}$  and while  $i \neq 0$  iteratively update  $q_i^{(\tau)}$ 
    as  $q_i^{(\tau+1)} = \frac{\mu_i}{t_i^{(s)}} - \frac{1}{M_{ii}}(M_{ij}q_j^{(\tau)} + \sigma_i^2)$ ;
    project  $q_i^{(\tau+1)}$  into power constraint interval  $[0, q_{i,max}]$ ;
    calculate new assignment for clusterhead( $i$ );
  end if
  calculate LADATMi value on channel  $c$  and corresponding priority for each group;
  repeat  $q_i^{(\tau+1)} = q_i^{(\tau)}$  until  $q_i^{(\tau)}$  converges;
  if no channel overloaded
    return;
  end if
  if feasible
    select adjustment candidate with minimal LADATMi value and begin negotiation;
  end if
  if  $(p_i^*, m^*, p^{coop}, n^*)$  does not change
    rate  $s[m]$  and let  $bcm_i = \frac{\mu_i SNR_i^{(\tau+1)}}{1 + SNR_i^{(\tau+1)}} + \frac{SNR_i^{(\tau+1)}}{M_i M_2 q_i^{(\tau+1)}}$ ;
  end if
  analyze the contention of links on channel  $c$  in two hop range;
  if  $i$  is bound to nodes of neighboring cluster
    assign  $i$  and make the channel assignment from its neighbor assignment;
  end if
  clusterhead( $i$ ) {
    for  $i \in N_s$ 
      if  $Prand(N_s) < W(i)$  and priority of  $i$  is not  $\emptyset$ 
        recover  $N_s$ ;
      end if
      if  $Load(I_i) < N_r$ 
        then select adjustment candidate with minimal load and begin distribution;
      end if
    }
  end
}

```

In this scheme, the non-forwarding action is always in Nash equilibrium. The topology construction is performed during the network initialization phase when no user traffic is present in the network. To fully reduce the co-channel interference and achieve higher gains in network performance, the topology attributes and the power constraints are jointly considered to exploit not only the channel diversity but also the spatial reusability. First, we sort all the node pairs in ascending order according to their minimum distance. Secondly, LADATM<sub>*i*</sub> runs on every node in the network to check whether the flows can all be routed. The sleep-awake cycles between neighbors are coordinated and generally accomplished through schedule exchanges. In case of dynamic duty cycles based on perceived values of instantaneous or time-averaged end-to-end latency, the overhead of passing frequent schedules also needs investigation in light of the ongoing high data rate message. The operation should be terminated when the transmission power reaches the maximum.

If we define  $U_{app}$  as the union of  $U_s^{mh}(p^{coop}, n)$  and  $U_r^{mh}(p_i, m)$ , then  $G_2$  is a spanning subgraph of all nodes. Therefore, the 2-connectivity of  $c \in \{c_1, c_2, \dots, c_L\}$  implies the 2-connectivity of  $U_{app}$ . Thus, there exists a 2-connected spanning subgraph and we have

$$c(U_{app}) = \sum_{i=1}^2 c(G_i) \leq |J_{opt}|, \quad (12)$$

where  $J_{opt}$  is the greatest common divisor of  $J_{prio}$ . The main part of the scheme requires  $O(n^2)$  time to construct the complete graph. Clusterhead  $i$  of the scheme requires  $O(n^4 + |J_{opt}|)$  time, where the  $O(n^4)$  term is due to the loop over the  $O(n^4)$  edges in  $G_1$ , and the  $O(|J_{opt}|)$  term is due to the deployment of  $J_{prio}$ . Note that  $\Theta(|J_{opt}|)$  time is required for the scheme to deploy  $J_{prio}$ . If we are only interested in the 2-connected spanning subgraph  $G_2$ ,  $O(n^2)$  time is sufficient.

We can compute the 2-approximation  $bcm_i$  with the help of the proposed scheme, but it is not necessary to give a theoretical proof. It was observed in [6] that the neighboring cluster of  $G_1$  provides a 2-connected spanning subgraph whose cost is often very close to that of the minimum cost 2-connected spanning subgraph of  $G_2$ . Therefore, LADATM<sub>*i*</sub> uses the neighboring cluster as a candidate for  $G_1$  instead of using a 2-approximation to the minimum cost 2-connected spanning subgraph. The topology and power consumption of each node can be optimized due to the minimum link occupation. The power update is the best response of the link player for a given tax rate and the assessment of others' actions. Tax rates convergence can be induced to the stable Nash equilibrium. Such an equilibrium strikes a balance between the minimized interference and the maximized rate.

### 3. Cross-Layer Communication Architecture

Appropriate weighting and seamless integration with the suitable channel access policy allows adjustments to be made to the energy-latency-fidelity trade-off space. Existing solutions often do not provide adequate support for broadband applications since the resource management, adaptation, and protection strategies available in the lower layers of the stack are optimized without explicitly considering the specific characteristics of hybrid USNs. Similarly, data compression and streaming algorithms do not consider the mechanisms provided by the lower layers for error protection and resource allocation. Using our proposed cross-layer communication architecture, it is possible to adapt LAD-CCSS for greater energy savings, although this is achieved at the cost of a bounded increase in the worst-case packet latency. We assume that the channel error is fully predictable at any time, and the proposed architecture's practical implementation shows marked deviations from the idealized case in terms of complexity. Bounds on various performance measures, such as delay and queue length can be derived at each element of the network, and thus, the QoS of the flows can be specified. Figure 4 outlines the proposed architecture.

The proposed architecture provides QoS support at the network layer. It interacts with the network and physical layer to realize the route change, as well as channel and power adjustment. The joint adjustment layer is not tied to any specific channel access algorithm. It can work with various access schemes that are applicable to multi-channel environment. The interaction with the network layer focuses on scheduling adjustment. There are two types of scheduling. The first type only adjusts the outgoing traffic interface and leaves the whole path unchanged. The other type replaces the original link with a multi-hop path. No modifications are required in the MAC layer. The network layer QoS support is enforced by a cross-layer control subsystem. This is achieved by the controlling operations and the interactions of the functionalities at the physical, MAC, and network layers, based on the unified logic of the cross-layer controller. The controller manages resource allocation, adaptation, and protection strategies based on the state of each functional block. All the decisions are jointly taken at the controller. The implementation of different functionalities is kept separate for ease of design and upgradeability. Thus, loss recovery and rate adaptation can be optimally handled, thereby avoiding feedback overheads latency, and can be responsive to the dynamics of the wireless link using the information obtained locally.

The cross-layer control subsystem consists of six modules: link measurement, neighbor state exchange, node negotiation, next hop selection, power adjustment, and channel switching.

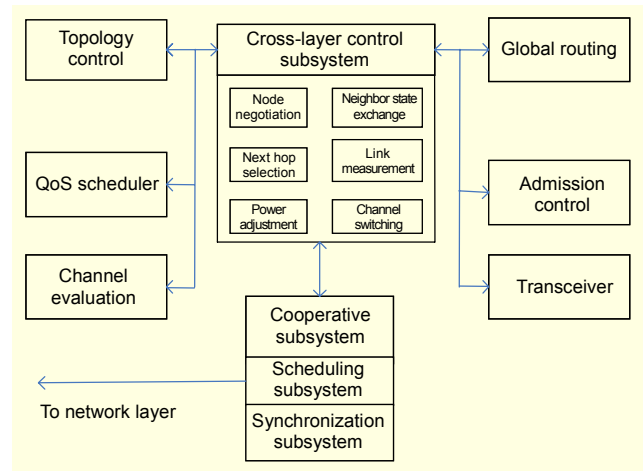


Fig. 4. Cross-layer communication architecture.

Among them, the link measurement module is utilized to collect the link status information. The estimation of the link packet loss ratio is based on the approach introduced in [11]. The next hops are selected by the cross-layer control subsystem by applying an admission control procedure that verifies each node on the path and checks that they are able to provide the required service level. The channel switching module allows delay calculated at each step based on the relative advance of each hop towards the destination. The time sliding window method is employed to measure the traffic rate on a link. In the neighbor state exchange module, each node broadcasts a HELLO message several times with different transmission power levels sequentially at the network setup phase. The specific power level of the source and previously inferred neighbor information from the received HELLO message are piggybacked in the next HELLO message. Through the information exchange, a node can get the basic neighbor state under different power levels at the beginning of the HELLO message transmission. After that, the node periodically broadcasts the traffic rate, the packet loss ratio for each active link, and the channel and power information to its neighbors. The information of its corresponding neighbor nodes is also piggybacked in this packet. In this way, the nodes can obtain the traffic and link status within multi-hop ranges. The node negotiation module is implemented to coordinate the nodes and complete the adjustment. The physical, MAC, and network layers together impact the contention for network resources. The physical layer has direct impact on the multiple accesses of the nodes in wireless channels by affecting the interference at the receivers. The MAC layer determines the bandwidth allocation to each transmitter, which naturally affects the performance of the physical layer in terms of successfully detecting the desired signals. On the other hand, as a result of the transmission schedules, high packet delays or low

bandwidth can occur, forcing the upper layer to change its route decisions.

The candidate receivers evaluate the channel condition based on the physical layer analysis of received RTS messages. If the channel quality is better than a certain level, a given receiver is allowed to transmit CTSs. The closer a receiver address is to the top of the receiver list, the higher its priority to access media. To prioritize the receivers, various  $N_s$  and  $LADATM_i$  are employed. The receiver with highest priority among those who have capability to receive data packets replies by sending a CTS first. Since all candidate receivers are within one-hop transmission range of the transmitter, and the carrier sensing range is normally two hops wider than the transmission range, the CTS should be powerful enough for all other qualified candidate receivers to sense the carrier. These receivers yield the opportunity to the one transmitting the CTS in the first place, and the  $J_{prio}$  with good channel condition remains the highest priority. The maximum candidate receiver list is scheduled if there are enough data packets targeting it. A longer receiver list means more diversity can be exploited. It also means that the waiting time increases before the transmitter can make sure that there is no qualified receiver. We assume that the probabilities for candidate receivers to successfully receive the intended data packet are identical and independent. In our simulations, the platform already yields significant throughput gains under the 4,096 flows condition, which will be discussed in section IV. Multicast RTS and prioritized CTS with channel awareness parallelize the multiple serial RTS/CTS messages so that the overhead of channel contention and channel probing can be reduced. More importantly, cooperative scheduling can be improved and can account for a dynamically changing topology due to nodes dropping out or new ones being added.

#### IV. Simulations and Discussion

The terrain model we used was a 10 km×7.5 km rectangular area with 12 dual rings in the multi-scenario. In each dual ring set, 7 cells are deployed on which the nodes pseudo-randomly move along the cluster cells under  $NS-2$ . All the links between the nodes are bi-directional. Each cell has a base station with an omnidirectional antenna at the center, and its radius is 1.25 km. Each base station has 2,048 available data channels. All the nodes can support the cross-layer communication architecture described in section III. As for the handoff mechanism, hard handoff was used in the evaluation model and the connectivity was considered under the Poisson Boolean model in this kind of sparse network. We used 4,096 TCP flows in the multi-scenario, and the simulation time for each point was 7,200 s.

We assumed that the power consumption is based on the distance from the transmitting nodes to the base stations.

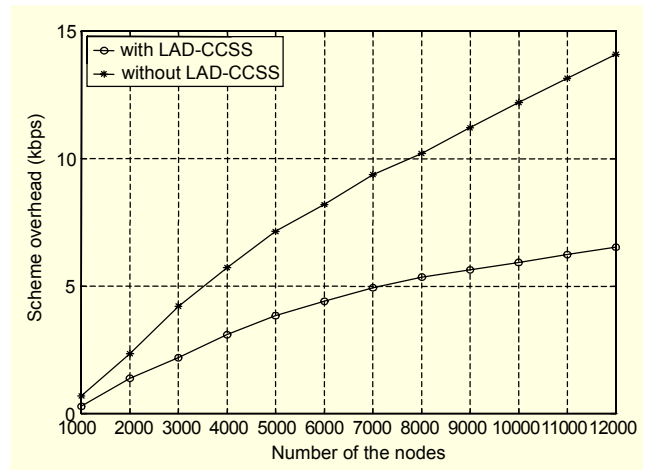


Fig. 5. Scheme overhead with various numbers of nodes.

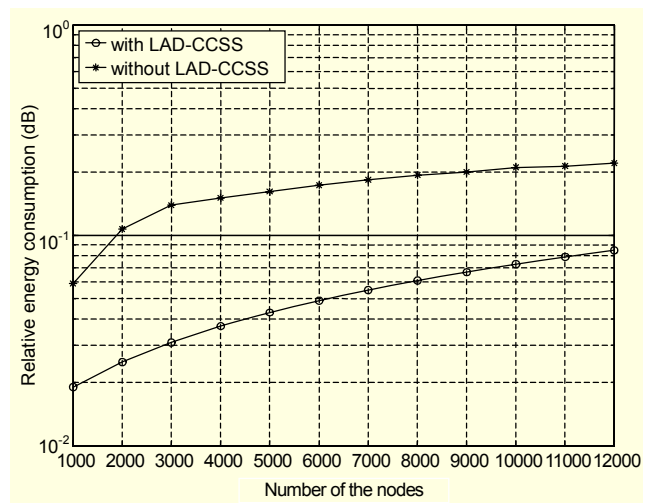


Fig. 6. Relative energy consumption with various numbers of nodes.

Employing the proposed scheme, the scheme overhead and the relative energy consumption were examined with various numbers of nodes. In Figs. 5 and 6, we compare the throughput of the proposed scheme with and without LAD-CCSS. As expected, the use of the proposed scheme can optimize the available channel capacity and the relative performance.

Figure 5 plots the overhead for the scheduling adjustment. The overhead includes the cost of sending a link probe packet to measure packet loss ratio, neighbor information exchange, and adjustment negotiation. The aggregated scheme overhead increases monotonically with the number of the nodes. Nevertheless, the overhead per node remains small, and only a small fraction of the available channel capacity is consumed. The network can tolerate more hops to support reliable transportation with the help of LAD-CCSS, which can make the network more stable and can support more hops. The maximal optimization is



about 24.16%. The reason for the improvement with the proposed scheme could be the following. Packet loss, especially burst packet loss, is the key factor in the multi-scenario that leads to the instability and unfairness observed at TCP. Data dropping at the MAC level due to the maximum allowable RTS retransmission times or resource scheduling times being exceeded can be optimized by LAD-CCSS.

Figure 6 gives the relative energy consumption with various numbers of the nodes. As the relative gain increases, the achievable rates increase accordingly. LADATM<sub>i</sub> with the cooperative scheduling scheme performs better than the one without LAD-CCSS, which only outperforms the strategy game. For large numbers of nodes, the ratio is approximately 4 dB; hence, the gain in total energy consumption for the reliability balancing strategy is 32.4%. The gain in the network lifetime is more significant, and it is determined by the lifetime of the current node. Notice that the two curves are independent of the channel states because they assume a perfect condition. The proposed scheme is virtually identical to cooperative scheduling until the point at which the power gain comes very close to real utility. Thus, it seems that cooperation is not necessary in the proposed scheme, especially when the gain is interrupted by the addressing ratio and the permitted hops.

We also compare the link reception probability and the end-to-end blocking probability separately with various numbers of nodes in Figs. 7 and 8.

Figure 7 plots the link reception probability with various numbers of nodes. When the number of nodes is less than 4,000, the link reception probability with LAD-CCSS is more than 90%. This is sufficient to support link measurement because of the small value of the flow requirement. When the number of nodes is more than 4,000, the channel states heavily depend on the load of the networks, but the reliable transportation requirement is

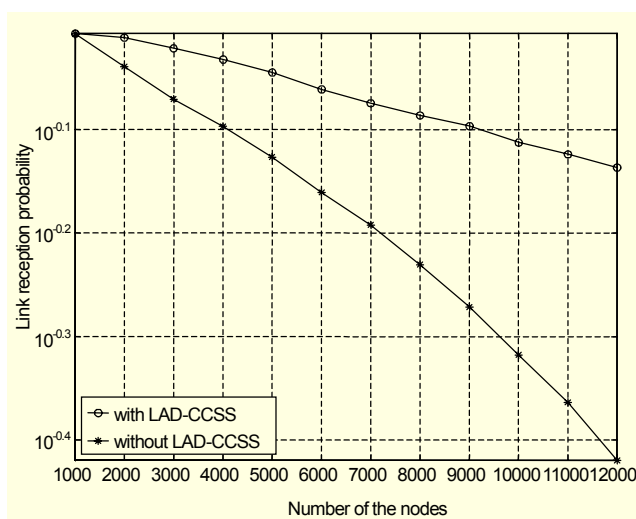


Fig. 7. Link reception probability with various numbers of nodes.

avoided with the help of cooperative scheduling. The maximal optimization is 16.32%, and the energy consumption increases linearly with the node number. The performance of the system without LAD-CCSS is not competent.

The clear benefits of the proposed scheme are the enhanced physical layer performance and the reduction by half of the order of the networking problem.

Figure 8 gives the end-to-end blocking probability with various numbers of nodes. When the number of nodes is less than 6,000, the probability of the end-to-end blocking is quite low because the throughput and congestion are actually in idle states. This is reasonable because no multiuser diversity gain can be achieved when only one user has a longer scheduling time than that of the MAC. When the number of nodes increases, the throughput gain resulting from the opportunistic scheduling starts to become evident. When the number of nodes increases to 6,000 or more, the probability of end-to-end blocking exceeds 0.05% and the gain stays relatively stable. The maximal optimization is 14.06% when the number of the nodes reaches 12,000. Moreover, the addressing ratio of success with unchanged parameters and external information can also be increased. The reason is that the probability that all candidate receivers will not be satisfied to receive a packet at any given time is very low. When the number of nodes increases, almost every time access point sends RTSs and receives CTSs to continue data delivery. If more flows are setup between randomly chosen node pairs, the traffic load of each flow will be high and the end-to-end probability that a packet will be generated at the node will increase monotonically. It is apparent that the system with LAD-CCSS offers significantly better performance than those without LAD-CCSS. On average, the performance is two times better

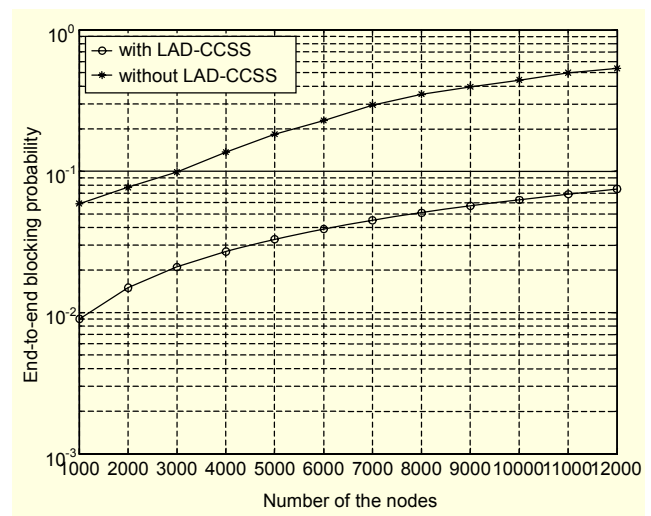


Fig. 8. End-to-end blocking probability with various numbers of nodes.

with the proposed scheme.

## V. Conclusion

In this paper, a performance evaluation metric and a cooperative cross-layer scheduling scheme was proposed. The proposed scheme was compared to other schemes through simulation, and its superiority was demonstrated by analysis of the simulation results. Based on the simulation results, the scheme overhead, the relative energy consumption, the link reception probability, and the end-to-end blocking probability were improved. The addressing ratio of success with unchanged parameters and external information can be increased, and the network can tolerate more hops to support reliable transportation with the help of the proposed scheme. The scheme can make the network stable and able to support more hops. To sum up, the proposed scheme can enhance the average rate performance of hybrid USNs and stabilize the outage probability stable.

## References

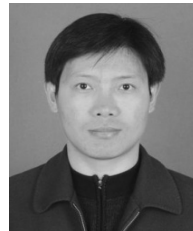
- [1] S. Poha, T.L. Porta, and C. Griffin, *Sensor Network Operations*, Wiley-Interscience, NJ, USA, IEEE Press, 2006.
- [2] G. Sharma and R. Mazumdar, "Hybrid Sensor Networks: A Small World," *ACM MobiHoc*, May 25–27, 2005, Chicago, Illinois, USA. pp. 366-377.
- [3] O. Akan and I.F. Akyildiz. "Event-to-Sink Reliable Transport in Wireless Sensor Networks," *IEEE/ACM Trans. Networks*, vol. 13, no. 2, 2005, pp.1003-1017.
- [4] W. Ye, J. Heidemann, and D. Estrin. "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE Trans. Networks*, vol. 12, no. 3, 2004, pp. 493-506.
- [5] Z.F. Diao, D. Shen, and V.O.K. Li, "CPLD-PGPS Scheduler in Wireless OFDM Systems," *IEEE Trans. Wireless Communications*, vol. 5, no. 10, 2006, pp. 2923-2931.
- [6] M. Chiang, "Balancing Transport and Physical Layers in Wireless Multihop Networks: Jointly Optimal Congestion Control and Power Control," *IEEE Journal on Selected Areas Communications*, vol. 23, no. 1, 2005, pp. 104-116.
- [7] C. Saraydar, "Efficient Power Control via Pricing in Wireless Data Networks," *IEEE Trans. Communications*, vol. 50, 2002, pp. 291-303.
- [8] C. Chekuri et al., "Non-Cooperative Multicast and Facility Location Games," *IEEE Journal on Selected Areas Communications*, vol. 25, no. 6, 2007, pp. 1193-1206.
- [9] H. Wu and F. Yang, "Distributed Channel Assignment and Routing in Multi-radio Multi-channel Multi-hop Wireless Networks," *IEEE Journal on Selected Areas Communications*,

Special Issue on Multi-hop Wireless Mesh Networks, vol. 24, 2006, pp. 1972-1983.

- [10] L. Hu, "Topology Control for Multihop Packet Radio Networks," *IEEE Trans. Communications*, vol. 41, 1993, pp. 1424-1481.
- [11] M. Takai, J. Zhou, and R. Bagrodia, "Performance Evaluation of Directional Adaptive Range Control in Mobile Ad Hoc Networks," *Wireless Networks*, vol. 11, 2005, pp. 581-591.



**Yingji Zhong** received the PhD degree from the School of Information Science and Engineering, Shandong University, China in 2005. He is an assistant professor in the School of Information Science and Engineering, Shandong University, China, and a post-doctoral researcher with UWB-ITRC, Inha University, Korea. He is a reviewer for several IEE and IEEE journals. He is the session chair of IEEE ICACT. He has published more than 30 papers in international journals and conference proceedings. His research interests include wireless multimedia sensor networks, wireless ad hoc networks, topological analysis, and QoS.



**Qinghai Yang** received the BS degree in communication engineering from Shandong University of Technology, China, in 1998, the MS degree in information and communication systems from Xidian University, China, in 2001, and the PhD in communication engineering from Inha University, Korea, with the university-president award in 2007. From March 2007 to February 2008, he was a research fellow at UWB-ITRC, Korea. He is now with Xidian University as an associate professor. His current research interests are cooperative MIMO-OFDM, cooperation and competition in dynamic spectrum access networks, and MIMO UWB systems.



**Kyung Sup Kwak** received the BS degree from the Inha University, Incheon, Korea, in 1977; the MS degree from the University of Southern California, in 1981; and the PhD degree from the University of California at San Diego, in 1988. From 1988 to 1989, he was a member of technical staff at Hughes Network Systems, San Diego, California. From 1989 to 1990 he was with the IBM Network Analysis Center, North Carolina. Since then, he has been with the School of Information and Communication, Inha University, Korea, as a professor. He was the chairman of the School of Electrical and Computer Engineering from 1999 to 2000 and the dean of the Graduate School of Information Technology and Telecommunications from 2001 to 2002. He is the current director of the Advanced IT Research Center of Inha University, and the UWB Wireless Communications Research Center, Korea. Since 1994, he has

served as a member of the Board of Directors, and from 2000 to 2002, he was the vice president for the Korean Institute of Communication Sciences (KICS), where he was president in 2006. In 1993, he received the Engineering College Young Investigator Achievement Award from Inha University and a distinguished service medal from the Institute of Electronics Engineers of Korea (IEEK). In 1996 and 1999, he received Distinguished Service Medals from the KICS. He received the Inha University Engineering Paper Award and the LG Paper Award in 1998 and the Motorola Paper Award in 2000. His research interests include multiple access communication systems, mobile communication systems, UWB radio systems, ad hoc networks, and sensor networks. Professor Kwak is a member of IEEE, IEICE, KICS, and KIEE.



**Dongfeng Yuan** received his MS degree from Shandong University, China, in 1988, and his PhD degree in electrical engineering from Tsinghua University, China, in January 2000. Prof. Yuan is now a full professor and dean of the School of Information Science and Engineering of Shandong University, China. He

has been a senior member of IEEE since 2001 and is a senior member of China Institute of Communications (CIC) and China Institute of Electronics (CIE). As a professor he has taught at the University of Calgary, Canada; the University of Michigan, Ann Arbor, USA, and Agder University, Norway. He has been invited to give over 20 talks in many countries. He has served as a TPC member for conferences including IEEE ICC'2007, IEEE WCNC'2007, IEEE VTC'2001, and IEEE PIMRC'2003. He is an editor for *International Journal of Communication Systems* and *Journal of Wireless Communications and Mobile Computing*. He has published 4 books, 14 patents, and over 200 technical papers in journals or international conference proceedings. His research interests include channel modeling, multilevel coding and multistage decoding, MIMO techniques, turbo and LDPC codes, joint source and channel coding, OFDM and multicarrier modulation, adaptive modulation and coding, cross-layer design, radio resources management, and cognitive radio.