A novel framework of routing policy for energy-efficient wireless sensor networks: Progress-based nearest forwarding

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Abstract: A number of battery-driven sensor nodes are deployed to operate a wireless sensor network, and many routing protocols have been proposed to reduce energy consumption for data communications. This letter proposes a novel routing framework for multihop networks, which is based on transmission power control, nearest forwarding and packet progress toward a sink, in consideration of reducing the extra number of hops in the networks. The energy consumption for the topology employing the proposed forwarding is evaluated by simulation, and it is shown that the proposed scheme is more energy-efficient than the shortest-path tree constructed by Dijkstra’s algorithm.

Keywords: wireless sensor network, multihop communication, routing, energy efficiency

Classification: Network

References


1 Introduction

There have been many routing protocols for wireless ad-hoc/sensor networks in literature. One of the most empirical packet forwarding methods in location-aware protocols is the greedy forwarding, in which a forwarding node can make a locally optimal choice in choosing a next-hop node. The locally optimal choice is the neighbor geographically closest to the destination/sink [1], and thus it is based on packet hop progress toward the destination. This locally optimal choice means that the greedy forwarding is based on the disk model (or protocol model), i.e., each node has the same transmission power and limited common communication range. Although this forwarding policy can minimize the remaining distance to the destination in each hop [2], there occurs the dead-end problem, where a node cannot deliver data to the sink despite the existence of another route which can reach the sink. Moreover, the connectivity between two arbitrary nodes cannot be guaranteed when the network is quite sparse, resulting in the emergence of isolated nodes.

Power saving of sensor nodes is a problem of vital significance for providing beneficial services in wireless sensor networks (WSNs). Routing protocols with (variable-range) transmission power control (TPC) are an alternative choice which aims at guaranteeing both energy efficiency and network connectivity. TPC sets the
radio transmission power of each node to the right level according to the communication distance, which enables preventing the networks from the dead-end problem. In [3], TPC mechanism is implemented in AODV routing protocol for mobile WSNs, and it is shown that the implementation of TPC has some impact on the networks in respect to energy consumption. In [4], the minimum spanning tree rooted at one source node is constructed on the basis of TPC, and it is clarified that compared to the disk model, the variable-range strategy can save transmission power, as well as improving the traffic capacity.

We can divide routing policies into three types: random-, furthest- and nearest-neighbor forwarding. Random-neighbor forwarding is a concept often used to model network processes like distributed localization and flooding, while furthest- and nearest-neighbor routing are often design choices for packet hopping/routing [5]. Here, furthest-neighbor forwarding is the same framework as the greedy method referred to above. Nearest-neighbor forwarding is applied to the literature [6, 7, 8], and it is said to achieve a good performance under energy consideration for most scenarios [6, 7].

In this letter, we propose a novel framework of simple packet forwarding strategy. The proposed routing scheme is cherry-picking: the features applied are progress-based routing, variable-range TPC, and nearest-neighbor forwarding. It defines the forwarding angle to search for next-hop relay nodes. Simulation results compare the proposed routing strategy with a shortest-path tree (SPT). The SPT scheme simulated in this letter also performs TPC, but does not follow either nearest-neighbor forwarding or hop progress. Instead, it constructs a tree structure rooted at the sink such that the sum of costs is minimized (to be described later).

2 Proposed routing policy

For efficient routing, progress should be made at each hop, i.e., the next-hop neighbor should be closer to the sink [11]. When constructing multihop routes, however, some routing protocols possibly have the hops in which the next-hop node is farther from the sink than the previous node. For instance, SPT-based topologies [10] generally optimize distance-based costs for constructing multihop paths, which may lead to the emergence of regress hops, some of which are to be found in Fig. 1(a). This SPT minimizes the summed cost $\sum_{i=1}^{N_H} r_i^\alpha$ by Dijkstra’s algorithm [9], where $r_i$ is the $i$-th hop Euclidean distance, $N_H$ is the hop-count and $\alpha$ is the path-loss exponent, to connect all nodes in a network to the sink. Consequently, although the energy required for data transmission can be optimized at each path, the number of hops increases, resulting in an inefficient detour routing in terms of energy consumption. Therefore, we propose the progress-based nearest forwarding (PNF) routing as a routing framework for energy-efficient WSNs.

Fig. 1(b) illustrates PNF routing policy. PNF routing considers a neighborhood area toward the sink for each node to search for the next-hop node. The neighborhood area has an angle defined by $\phi$, where $0 \leq \phi < \pi/2$ to guarantee hop progress. Note that the opening angle of every neighboring sector is $2\phi$, i.e., the neighboring sector becomes a semi-circle if $\phi = \pi/2$. Thus, any node located outside the neighborhood area is passed over for the next-hop candidate even if it is the
nearest from the previous node. Fig. 1(b) shows PNF routing for $\phi = \pi/4$, which has a fan-shaped sector with an opening angle of $\pi/2$ toward the sink for each hop. We choose the angle as $\phi = \pi/4$ for the practical range of neighborhood used in this letter. Assuming that nodes in a network are distributed according to the two-dimensional Poisson point process with intensity $\rho$ [11], the probability density function of hop distance and the expected hop distance in PNF routing are given by

$$f(r) = 2\rho r e^{-\rho r^2},$$

$$E[R] = \frac{1}{2} \sqrt{\frac{\pi}{\rho \phi}},$$

respectively. Especially for $\phi = \pi/4$, the hop distance follows the Rayleigh distribution with $E[R] = 1/\sqrt{\rho}$.

Although following nearest-neighbor forwarding, PNF routing does not immediately make the number of hops increase. This is because it is based on hop progress and the forwarding angle $\phi$. The smaller number of hops means the longer progress per hop and the smaller latency. (The evaluations on them are not included in this letter.) On the other hand, WSNs with the larger number of hops are likely to have smaller energy consumption per hop due to short hops. We show the energy efficiency for the whole network in simulation results to be described, in terms of whether multihop routing topologies should have the smaller (PNF) or larger (SPT) number of hops.

When it comes to construct location-based packet forwarding topologies such as SPT and PNF, location information on all nodes and the sink is required. It is achieved by measuring the received signal strength from other nodes and the sink, and/or using geographical location service [12]. In addition, considering a location-based TPC mechanism for routing, overhead energy for channel state estimation has an effect on the total energy consumption. Giving the same number of nodes and the same node arrangement, however, both PNF and SPT routings have the same number of edges (links) in the network, leading to the same additional energy budget for location information retrieving and channel state estimation. Therefore we can have a consequence that the fair premise in both routing policies results in
an impartial energy addition, and we omit the consideration of those kinds of extra energy budgets from this letter.

### 3 Performance evaluations

We compare the energy consumption of all the nodes in the network for SPT and PNF routing. One sink and $N$ nodes are deployed in a square network area, with the sink at the origin $(0, 0)$ and the nodes randomly distributed (see Fig. 1). Each node aggregates data from its children and its own sensed data into one packet, and transmits it to its parent. We set the payload length and the header length as $S = 500$ bytes and $H = 25$ bytes, respectively. We also set the energy for data communication per bit and data aggregation per bit as $E_{elec} = 50$ nJ/bit and $E_{agg} = 5$ nJ/bit, respectively. Note that the two-ray ground reflection model is used for radio propagation; therefore, the energy required for data reception $E_R$, data sensing/aggregation $E_A$ and data transmission $E_T$ at each node are calculated as

$$E_R = (N_dS + H)E_{elec} \cdot (1 \{N_d > 0\})$$

$$E_A = (N_d + 1)SE_{agg}$$

$$E_T = \begin{cases} 
((N_d + 1)S + H)(E_{elec} + \epsilon_{fr}r^2), & \text{for } r < r_0, \\
((N_d + 1)S + H)(E_{elec} + \epsilon_{mp}r^4), & \text{for } r \geq r_0,
\end{cases}$$

where $N_d$ is the number of descendent nodes, $\epsilon_{fr} = 10$ pJ/bit/m$^2$ is the free-space propagation loss coefficient, $\epsilon_{mp} = 0.0013$ pJ/bit/m$^4$ is the multipath propagation loss coefficient, $r$ is the transmission distance, and $r_0 = \sqrt{\epsilon_{fr}/\epsilon_{mp}}$ is the break point at critical distance. Also, $1\{\cdot\}$ denotes the set indicator function. As for energy parameters, we use the energy model in [13] which has been widely adopted to studies in WSNs to determine each type of energy mentioned above. We do not count the extra energy consumption due to overhearing nodes or packet retransmissions, as well as the energy for node localization and channel state estimation, in order to focus on and investigate the energy consumed in the phase of data forwarding. Energy consumption is evaluated over 10,000 independent random realizations.

Fig. 2 illustrates the energy reduction rate $ERR$ [%],

$$ERR = \left(1 - \frac{E_{total}^{PNF}}{E_{total}^{SPT}}\right) \times 100,$$

where $E_{total}^{SPT}$ is the energy required for SPT routing, and $E_{total}^{PNF}$ is for PNF routing. $ERR$ describes how much energy consumption is reduced in PNF routing compared to SPT. It can be seen from Fig. 2 that PNF routing is more energy-efficient than SPT in all cases of interest. PNF routing reduces energy consumption by at least 8.64% of SPT, and at most 30.2%. In addition to that, it is noteworthy that the reduction rate is dependent on the node density of the network. Generally, the energy reduction effect is larger as the number of nodes increases. This is due to the larger number of hops in larger-density networks. The energy reduction is attributed mainly to the reduction of the number of hops. Fig. 3(a) and 3(b) show the maximum number of hops in the network and the total energy consumption for SPT and PNF routing, respectively. It can be seen that although the number of hops
increases in accordance with the number of nodes for both routing policies, PNF routing always results in the smaller hop-count than SPT. For a network with 20 and 300 nodes in a side length of 100 m, the hop-count reduction rate is 20.9% and 30.0%, respectively. PNF realizes short routes in terms of energy consumption by considering not only energy for data transmission but also hop progress, which leads to preventing its network routing from becoming detour paths. From these observations, it is clear that the hop-count reduction based on hop progress of PNF routing effectively reduces the energy cost for data forwarding.

4 Conclusion

This letter proposed a novel framework for energy-efficient routing policy in WSNs. The proposed method, named PNF routing, is based on variable-range TPC, nearest-neighbor routing, and progress toward a sink at each hop in order to reduce the extra number of hops. Performance evaluations showed that energy consumption in WSNs which employ PNF routing is less than SPT routing, with the energy reduction rate of at least 8.64% for the networks of interest. To further realize the network topology with minimum energy consumption, the forwarding angle for PNF routing is to be optimized.

Fig. 2. A color map describing the energy reduction rate from SPT to PNF.

Fig. 3. Maximum number of hops and total energy for SPT and PNF in a 100 m × 100 m network.
Direction finding of multiple targets using coprime array in MIMO radar

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Abstract: We propose a novel direction finding algorithm by exploiting a coprime array configured at the receiver of a transmit-diversity multiple-input-multiple-output (MIMO) radar system. The algorithm uses the interference set of virtual sensor positions in coprime array to construct an observation vector which behaves like a data vector obtained from a uniform linear array (ULA). Then the forward-backward spatial smoothing and shift-invariance techniques are combined to effectively estimate the angles of multiple targets. The maximum number of identifiable targets is analyzed. Compared with conventional ULA-based algorithm in MIMO radars, the proposed algorithm can achieve larger array aperture and higher spatial resolution.

Keywords: MIMO radar, direction finding, coprime array, virtual aperture, spatial resolution

Classification: Antennas and Propagation

References


1 Introduction

Multiple-input-multiple-output (MIMO) radar and its application in direction finding (DF) and target localization have drawn significant attention recently [1, 2, 3]. In [1], the signal model of MIMO radar with transmit diversity has been presented to improve the performance. In [2], the DF in transmit diversity MIMO Radar has been evaluated. The model in [2] has been extended to multiple targets scenario, a DF algorithm is proposed in [3] based on MUSIC algorithm exploiting uniform linear array (ULA) at the receiver. However, ULA is limited when the number of targets is equal or even larger than that of the receive sensors. Unlike the ULA, the non-uniform linear array (NLA) is composed of the sensors with positions being not a series of consecutive integers with respect to half carrier wavelength. As an emerging NLA, the coprime array [4, 5, 6] can greatly increase the array aperture based on the concept of coarray. In [4], a coprime array is proposed for DOA estimation with MUSIC algorithm. However, peak searching is needed, and its virtual array aperture is reduced by spatial smoothing.

In this article, a novel MIMO radar DF algorithm is proposed based on coprime array. In our model, the transmit antennas are widely spaced to enable transmit diversity, while the receiver is configured with a coprime array to enable DF. Exploiting the inter-difference set of the virtual sensor positions in the coprime array, we extract the useful rows and construct an observation vector which behaves like a data vector obtained from a ULA. The angles of multiple targets can be effectively estimated exploiting the forward-backward spatial smoothing and shift-invariance techniques. No peak searching is needed. The maximum number of identifiable targets is analyzed.

2 Signal Model

Assume that the MIMO radar transmit array comprises \( K \) widely spaced sensors, and the receive array is configured with a coprime array having parameters \( M \) and \( N \), as illustrated in Fig. 1. There are \( N + 2M - 1 \) receive sensors, whose positions can be given by a set \( \mathcal{S} = \{ Mnd, 0 \leq n \leq N - 1 \} \cup \{ Nmd, 1 \leq m \leq 2M - 1 \} \), where \( M \) and \( N \) are two positive coprime integers satisfying \( 2 \leq M < N \), and \( d \) is a fundamental spacing. \( d = \frac{\lambda}{2} \), where \( \lambda \) is the wavelength. The receive sensor positions in \( \mathcal{S} \) are arranged in order and denoted by a set \( \mathcal{X} = \{ x_1, x_2, \ldots, x_{N+2M-1} \} \).

![Fig. 1. Coprime array with parameters \( M \) and \( N \)]
There are $P$ targets with direction $\theta_p$ for $p = 1, 2, \cdots, P$. For the transmit diversity MIMO radar, the receive signal in the $n$th snapshot is written as

$$
x(n) = \sum_{p=1}^{P} a(\theta_p) \alpha_p^T s(n) + w(n)
$$

where $x(n)$ is an $(N + 2M - 1) \times 1$ vector, $s(n)$ is a $K \times 1$ vector denoting the transmit waveform, $w(n)$ denotes the additive Gaussian noise which is uncorrelated with $s(n)$, and the $K \times 1$ vector $\alpha_p$ denotes the RCS fluctuations of the $p$th target. The $K$ elements of $\alpha_p$ are uncorrelated due to the transmit waveform orthogonality. For coprime array, the steering vector induced by the $p$th target is given by

$$
a(\theta_p) = [1, e^{-j2\pi \sin \theta_p x_1/i}, \cdots, e^{-j2\pi \sin \theta_p x_{K}/i}]^T
$$

Let $A(\theta) = [a(\theta_1), \cdots, a(\theta_P)]$, then $x(n)$ in (1) can be rewritten as

$$
x(n) = A(\theta) \begin{bmatrix} \alpha_1^T \\ \vdots \\ \alpha_P^T \end{bmatrix} s(n) + w(n) = A(\theta) \tilde{s}(n) + w(n)
$$

where $\tilde{s}(n)$ denote the equivalent source signal vector.

### 3 Direction finding in MIMO radar exploiting coprime array

#### 3.1 Construction of an observation vector

The covariance matrix of $x(n)$ is given by

$$
R_{xx} = E\{x(n)x(n)^H\} = A(\theta)R_{ss}A^H(\theta) + \sigma_w^2 I_{N + 2M - 1}
$$

$$
= K\sigma_w^2 \sum_{p=1}^{P} a(\theta_p)a^H(\theta_p) + \sigma_w^2 I_{N + 2M - 1}
$$

where $R_{ss}$ denotes the covariance matrix of $\tilde{s}(n)$. Its $(p, q)$th element is $R_{ss}(p,q) = E\{a_p^T s(n) a_q^H(n)\}$. If the $K$ elements of $\tilde{s}(n)$ are orthogonal with each other and have power $\sigma_w^2$, then $R_{ss}(p,q) = \begin{cases} K\sigma_w^2 & p = q \\ 0 & p \neq q \end{cases}$. $R_{xx}$ is then vectorized, i.e.,

$$
r = \text{vec}(R_{xx}) = V(\theta_1, \theta_2, \cdots, \theta_P)b + \Lambda \sigma_w^2
$$

where the $P \times 1$ vector $b = [K\sigma_w^2, \sigma_w^2, \cdots, \sigma_w^2]^T$ behaves as a signal vector, and $\Lambda \sigma_w^2 = [\sigma_w^2 L_1^T, \cdots, \sigma_w^2 L_{N + 2M - 1}^T]^T$ behaves as the noise vector, where $L_i$ for $i = 1, 2, \cdots, N + 2M - 1$ is a column vector with all zeros except one at the $i$th position. $V(\theta_1, \theta_2, \cdots, \theta_P) = [a_1^*(\theta_1) \otimes a(\theta_1), \cdots, a^*(\theta_P) \otimes a(\theta_P)]$. The $ij$th element of $a^*(\theta_p) \otimes a(\theta_p)$ can be denoted by

$$
a_i^*(\theta_p) a_j(\theta_p) = e^{-j2\pi \sin \theta_p x_{i,j}/i}, \quad 1 \leq i, j \leq N + 2M - 1
$$

It can be observed in (6) that $V(\theta_1, \theta_2, \cdots, \theta_P)$ behaves like a virtual array manifold having $(N + 2M - 1)^2$ virtual sensor positions. According to the property of co-array [5], its inter-difference set includes $2MN + 1$ consecutive integers in the integer range $[-MN, MN]$, which means that there exist $2MN + 1$ rows in $V(\theta_1, \theta_2, \cdots, \theta_P)$ with virtual sensor positions located at $\{-MN, \cdots, 0, \cdots, MN\}$. We extract these $2MN + 1$ rows from $r$ to form a new observation vector $\hat{r}$ with the
order of \([-MN_d, \cdots, 0, \cdots, MN_d]\). Thus, \(\hat{r}\) behaves like a data vector obtained from a \((2MN + 1)\)-sensor ULA.

### 3.2 Direction finding algorithm

At first, we define an \((MN + 1) \times (2MN + 1)\) selection matrix,

\[
J_n = \begin{bmatrix}
0_{(MN+1) \times (n-1)} & I_{MN+1} & 0_{(MN+1) \times (MN+1-n)}
\end{bmatrix}
\]  

for \(n = 1, \cdots, MN + 1\), and define

\[
\hat{Y}_{SS} = \begin{bmatrix}
J_1\hat{r} & \cdots & J_n\hat{r} & \cdots & J_{MN+1}\hat{r}
\end{bmatrix}
\]

\[
\hat{Y}_{FBSS} = \begin{bmatrix}
\hat{Y}_{SS} & \Pi_{MN+1}\hat{Y}_{SS}
\end{bmatrix}
\]

where \(\hat{Y}_{SS}\) and \(\hat{Y}_{FBSS}\) are the data matrices acquired by applying spatial smoothing (SS) and forward-backward spatial smoothing (FBSS) to \(\hat{r}\), respectively, and \(\Pi_{MN+1}\) is an \((MN + 1) \times (2MN + 1)\) exchange matrix with ones on its anti-diagonal lines and zeros elsewhere. Thus, the average covariance matrix of \(\hat{Y}_{FBSS}\) is given by

\[
R_{FBSS} = \frac{1}{MN + 1} \hat{Y}_{FBSS}\hat{Y}_{FBSS}^H
\]

When \(MN + 1 \geq P/2\), \(\hat{Y}_{FBSS}\) is a nonsingular matrix. Thus, perform eigenvalue decomposition on \(\hat{Y}_{FBSS}\). It’s largest \(P\) eigenvalues are given by \(\{\lambda_1, \lambda_2, \cdots, \lambda_P\}\), and its eigen vectors corresponding to the \(P\) eigenvalues form the signal subspace \(U_S = [U_{S1}, U_{S2}, \cdots, U_{SP}]\). Then, extract the 1st to \((MN)\)th rows from \(U_S\) to obtain matrix \(U_{S1}\). Similarly, extract the 2nd to \((MN + 1)\)th rows from \(U_S\) to obtain matrix \(U_{S2}\). According to the rotational invariance property, there exists \(U_{S2} = U_{S1}\Phi\), where the eigenvalues of \(\Phi\) are given by \(e^{j\omega_p}\), \(p = 1, 2, \cdots, P\), where \(\omega_p = \frac{2\pi}{\lambda} \sin \theta_p\). Then \(\theta_p\) is given by

\[
\theta_p = \arg \sin \left(\frac{\omega_p\lambda}{2\pi}\right), \quad 1 \leq p \leq P
\]

Assume that there are total of \(N + 2M - 1\) sensors at MIMO radar receiver. The maximum number of identifiable targets of the proposed method is \(\lfloor \frac{1}{2} (2MN + 1) \rfloor\) when \(MN + 1 \geq \frac{P}{2}\), where \(\lfloor \cdot \rfloor\) denotes the rounding function. Compared with ULA-based method in which only \(N + 2M - 2\) targets can be identified, the array aperture of our method is much larger.

### 4 Numerical simulation results

Assume that in coprime array, \(M = 5\), \(N = 7\) and \(N + 2M - 1 = 16\) sensors are configured at MIMO radar receiver. There are \(K = 3\) antennas for transmit diversity. 100 Monte-Carlo trials are conducted.

First, 15 targets with angles \(\{-45^\circ, -40^\circ, -35^\circ, -30^\circ, -25^\circ, -20^\circ, -15^\circ, 0^\circ, 15^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ, 40^\circ, 45^\circ\}\) are respectively estimated by a ULA (with \(d = \frac{\lambda}{4}\)) and a coprime array. SNR = 10 dB. The results are shown in Fig. 2(a)(b). Then, 27 targets with angles \(\{-75^\circ, -65^\circ, -55^\circ, -50^\circ, -45^\circ, -40^\circ, -35^\circ, -30^\circ, -25^\circ, -20^\circ, -15^\circ, -10^\circ, -5^\circ, 0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ, 40^\circ, 45^\circ, 50^\circ, 55^\circ, 65^\circ, 75^\circ\}\) are estimated using coprime array, as shown in Fig. 2(c). SNR = 10 dB. Finally, two closely located targets with angles \(\{10^\circ, 12^\circ\}\) are estimated using coprime array. The acquired RMSE versus SNR is shown in Fig. 3.
It illustrates that the performance of the proposed method outperforms the ULA-based method significantly. Multi-target direction finding is completed even when the number of targets \( P = 27 \) is larger than that of the sensors \( N + 2M - 1 = 16 \). Also, the MIMO radar system configured with coprime array can achieve higher spatial resolution than the conventional method under the same number of receive sensors.

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Effective data collection scheme for real-spatial group communication over hybrid infra-ad hoc wireless networks

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Abstract: This paper presents an effective data collection scheme to provide group communications among appropriate members selected by each user’s geographic situation and preference (real-spatial information). When each user directly notifies central servers of user’s information via wireless network infrastructure (Wi-infra), message delivery latency and losses drastically increase due to the network congestion. Therefore, we employ representative nodes (RNs) selected in a distributed manner. The RN first collects the real-spatial information from neighboring nodes via an ad hoc network and then notifies the server via Wi-infra. From simulation experiments, our scheme can drastically reduce both message delivery latency and losses.

Keywords: group communication, effective data collection, infra-ad hoc network

Classification: Network

References


1 Introduction

With the proliferation of high-performance handheld nodes, various types of communication can be provided anytime and anywhere. In particular, social network services provide communications for users around the world who have the same interests, preferences, and so on. However, the valuable information for each user is different depending on the user’s geographical situation and preference, which are referred to as “real-spatial information” in this paper. For example, when a foreign woman gets injury and is unable to move in the mountain, she wants to ask somebody for help who can satisfy all of the following conditions: (1) “having power to carry”, (2) “speaking the same language”, and (3) “being near here”. If we use the “twitter” application for help, we have to prepare suitable members by ourselves because “twitter” assumes communication in a pre-determined group. Therefore, we newly propose the “r-Space” system. The system can dynamically create user groups based on real-spatial information on demand to realize real-time communication among group members.

Fig. 1(a) shows the outline of the system, which consists of (I) the r-Space server and (II) (user) nodes. Note that the system holds Geographic Information System (GIS) information including “geographic” and “road” information. In addition, the nodes have two interfaces: an infrastructure (e.g., 3G and WiMAX) and an ad hoc network (e.g., WLAN).

The communication procedures are as follows. (i) The server collects node’s real-spatial information from all nodes. (ii) A node sends a demand for a group communication to the server. (iii) The server makes the new group among appropriate nodes selected based on the real-spatial information. (iv) The server notifies all group nodes of the group ID. (v) The node who sent a demand at phase (ii) can send a message to other group nodes with the group ID, leading to group communication. Because an effective collection of the nodes’ real-spatial information is essential, we propose a new data collection scheme.
2 Data collection scheme

2.1 Problem statement
The r-Space server should always correctly and promptly update nodes’ real-spatial information to provide real-time service, thus, nodes need to transmit their own real-spatial information as often as possible via the wireless network infrastructure (Wi-infra), which can cover a wide area effectively. However, in the Wi-infra, each node autonomously requests some wireless resources using random access channel method before transmitting data. Therefore, when a numerous number of nodes accesses the channel randomly, frequent request collisions would occur [1, 2]. Additionally, message delivery “latency” and “losses” increase drastically [3, 4] in this case. Our proposed scheme can effectively decrease them even if the huge number of nodes try to transmit their own message intensively, by using WLAN in combination with Wi-infra.

2.2 Related work
Here we review the existing studies for reducing message delivery latency and losses. Many studies proposed a frame aggregation scheme, which reduces overhead in wireless networks. Especially, Raghavendra [5] considered an ad hoc network, and Yu [6] considered a vehicular ad hoc network. However, they did not consider the Wi-infra, and only several papers have looked into Wi-infra. Luo [7] proposed the unified Cellular and Ad-Hoc Network architecture. They assumed
that each node has both a cellular interface and an ad hoc WLAN interface. Then, the selected proxy nodes forward the aggregated packets to the BS to improve the throughput performance. Furthermore, Law [8] proposed a hybrid cellular-ad hoc network in which tandem transmissions is employed to improve the data rate, the packet loss ratio, and so on.

Our research focuses on the number of competitive nodes in WLAN. The number is smaller than the number in Wi-infra because of WLAN’s narrow coverage. Therefore, WLAN is effectively used to reduce the number of competitive nodes in Wi-infra. None of the existing studies can effectively decrease both the latency and losses with this concept.

3 Proposed scheme
To solve the problems in Section 2.1, we propose a new data collection scheme utilizing the hybrid infra-ad hoc network as shown in Fig. 1(b).

In our proposed scheme, each node collects neighboring nodes’ real-spatial information by capturing messages periodically broadcasted over the WLAN ad hoc network whose channel is determined by our prior method [9]. After that, only representative nodes (RNs) concatenate the data collected from neighboring nodes and then transmit it to the BS which is connected with the r-Space server. As a result, the number of messages transmitted on the Wi-infra is drastically decreased.

3.1 Selection policy for an RN candidate
First, we hypothetically divide the entire area into “sub-areas” which are smaller hexagonal areas. Note that we assume that all nodes know the following information in advance: (1) “time” and “location” information (periodically (e.g., 1 s) obtained by GPS system), (2) “reference (starting) point” in the area, (3) radius of each sub-area. By using this information, each node can identify a sub-area to which it belongs. Moreover, the sub-area size should be wider to collect neighboring nodes’ information efficiently, and so the radius of individual hexagons is set to 150 m, which is the transmission range of the lowest PHY rate in WLAN (6 Mbps).

The RN has two roles: (I) information collection from other nodes in the same sub-area and (II) transmission of the concatenated message to the BS. The node closest to the center of the sub-area (center node) is able to achieve (I) reliably, whereas the node closest to the BS (closest node) is able to achieve (II) effectively. If the communication quality to the BS is sufficient, the center node can achieve both simultaneously. Otherwise, both the center node and the closest node are employed to achieve two roles, respectively. Note that these nodes are determined based on messages broadcasted in the distributed manner.

3.2 Decision on message transmission
To provide the service quickly, the real-spatial information of all nodes should be transmitted to the server sooner. Therefore, the RN candidate estimates the transmission latency when using the hybrid infra-ad hoc network and that when using the Wi-infra only, respectively.
$L_p$ is the transmission latency of “proxy transmission” by the RN and $L_d$ is the sum of latencies of “direct transmissions” from each node, where $L_p$ and $L_d$ are estimated based on the various parameters described below (See Eqs. (1) and (2)). Note that each node obtains the information from beacon packets in the Wi-infra and then notifies the information of the RN candidate via WLAN.

- Message size of real-spatial information: $msgSize$
- NodeID: $i$ ($r$ means an RN candidate)
- Number of nodes in a sub-area: $m$
- Data rate for each node: $dataRate_i$
- Number of frame transmissions: $n_i$
- Overhead of direct transmission: $t$

$$L_p = \left\lfloor \frac{(msgSize \times m)}{dataRate_r} \right\rfloor \times n_r + t$$  \hspace{1cm} (1)

$$L_d = \left\lfloor \sum_{i=1}^{m} \left\{ \frac{(msgSize/dataRate_i)}{n_i} \right\} \right\rfloor + t \times m$$ \hspace{1cm} (2)

If $L_p < L_d$, the RN candidate decides a proxy transmission and then notifies other nodes of this decision. Nodes who are notified do nothing. Otherwise, the RN candidate implicitly asks other nodes for direct transmission by timeout. Finally, the RN or each node begins to transmit a periodical message to the BS via Wi-infra.

## 4 Performance evaluation

### 4.1 Simulation model

The effectiveness of our proposed scheme is examined through a simulation experiment using QualNet ver. 5.2. Table I and Fig. 2(a) show simulation parameters and topology, respectively. One BS provides the service within a circle of a radius 1.5 km, where includes 111 sub-areas. We place 400 nodes so as to change node density depending on the distance from the BS because the node density tends to be high as the BS gets closer. The red, orange, and gray colors indicate the average density of 10 nodes, 5 nodes, or 1 node, respectively. We compare the performance of our proposed scheme and the “non-proposed scheme”, which all nodes are forced to transmit their own data without proxy transmission (our proposed scheme), in terms of the following measures. The average values of 10 simulations are shown in section 4.2.

- Number of transmitted messages
- Number of lost messages
- Message delivery latency

### 4.2 Simulation results

As shown in Fig. 2(b), since our proposed scheme collects neighboring nodes’ information and concatenates them into a single message, the number of transmitted messages is reduced by 74.5% (from 400 to 102). Note that the transmission collision ratio is inherently decreased, and so the number of lost messages can be reduced by 68.9% (from 195.6 to 60.8), as shown in Fig. 2(c). Message losses inevitably cause a longer waiting time so that the average delivery latency can be shortened by 75.7% (from 1.43 s to 0.35 s) due to a few message losses (See...
Finally, we can verify that our proposed scheme can drastically reduce not only the number of message losses but also the message delivery latency.

5 Conclusion

We proposed an effective data collection scheme to provide real-spatial group communication among appropriate members selected on the basis of real-spatial information. First, RNs of each sub-area are selected in a distributed manner as a result of message exchange over an ad hoc network. Then, the RN concatenates the collected neighboring nodes’ real-spatial information and notifies the concatenated message of the center server via the Wi-infra. The efficiency of our proposed scheme was shown by simulation.

Acknowledgments

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Analysis of the interference from GFDM to OFDM signals in same band

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Abstract: This paper focuses the interference from GFDM signal to already-existing OFDM signal when both signals coexist in same band, considering some migration scenario from 4G to 5G mobile system. After defining system model, the mathematical expression is derived theoretically and numerically verified by computer simulation. This mathematical expression indicates that the time difference does not affect the cross-correlation between GFDM and OFDM symbols, and that the interference decreases approximately by square of subcarrier interval between those symbols. Derived formula can be used not only for the interference evaluation in various configurations, but also for designing the waveform filter of GFDM.

Keywords: 5G, GFDM, OFDM, interference, cross-correlation

Classification: Wireless Communication Technologies

References

1 Introduction

Aiming at post 4G era, various multicarrier modulation schemes other than OFDM are being studied. FBMC (Filter Bank Multicarrier) [1], UFMC (Universal Filtered Multicarrier) [2], GFDM (Generalized Frequency Multicarrier Multiplexing) [3, 4] and so on are examples of these so called “New Waveforms”. Since these schemes have less OOB (out-of-band) emissions in general, more efficient spectrum usage is expected. On the other hand, inter-subcarrier interference occurs in such non-orthogonal schemes. When such non-orthogonal multicarrier schemes coexist with OFDM signal in the same band, this interference could be stronger than the OFDM signal because the OFDM assumes orthogonality between subcarriers. This case is, however, quite likely to occur in future, due to migration scenarios from 4G to 5G system. Although some numerical results have already been reported by computer simulation [5], an analytical approach is still essential to study or to design the coexisting multicarrier schemes.

This paper focuses on the interference from GFDM signal to already-existing OFDM signal when both signals coexist in the same band. After defining system model, the formula is derived theoretically in section 2, which is numerically verified in section 3. Through this work, some features are stated and concluded.

2 System model and interference analysis

2.1 Mixed transmission of multicarrier signals

Fig. 1(a) shows the concept of hybrid multicarrier system. At the transmitter side, a filtered multicarrier signal such as GFDM signal along with a conventional OFDM signal is generated. GFDM is provided for advanced receivers, while OFDM is for legacy receivers, i.e., Fourier transform reception. Note that the OFDM receiver can detect OFDM signals only. GFDM signal interferes with such legacy receiver’s detection. In Fig. 1(a), the \( m \)-th subsymbol \( s_{kG,m} \) at \( kG \)-th subcarrier in GFDM signal appears at legacy OFDM receivers as interference.

Let the maximum number of OFDM subcarriers be \( N_F \) which is equal to the effective length of OFDM symbol in samples, as shown in Fig. 1(b). In this figure, \( k_F \) (\( k_F = 0, 1, \ldots, N_F - 1 \)) indicates the OFDM subcarrier position.

As for GFDM parameters, let the maximum number of subcarriers be \( K_G \), considering \( kG \)-th GFDM subcarrier interfering \( kF \)-th OFDM subcarrier, where \( kG = 0, 1, \ldots, K_G - 1 \). The \( K_G \) is the length of GFDM subsymbol as shown in Fig. 1(b). The integer \( m \) indicates the GFDM subsymbol number ranging from 0 to \( M - 1 \). \( M \) is the total number of subsymbols in one GFDM symbol.

In generating GFDM signal, a waveform filter is used, whose impulse response \( h(n) \) is defined by:

\[
h(n) = \sum_{k'=-k_0}^{k_0} H(k') e^{j2\pi k'_n/c}
\]  

where \( n \) is the sample number corresponding to time, taking the values \( 0, 1, \ldots, N_G - 1 \). \( N_G \) is the length of a GFDM symbol in samples, which is \( M K_G \). \( H(k) \) is a frequency transfer function of the waveform filter. The parameter \( k_0 \) corresponds to the stop frequency of the waveform filter. For instance, in case of the filter with roll-off factor \( \alpha \):
The GFDM symbol is composed of $M K_G$ modulation symbols. Each modulation symbol is multiplied by the following complex coefficient at time $n$.

$$g(n) = h(n - m K_G) e^{j 2 \pi k_G n}$$

where $k_G$ and $m$ indicate the subcarrier number and the subsymbol number of the modulation symbol, respectively. Note that, some references, e.g. [3], in the definitions use opposite sign for the exponent in Eq. (3), i.e. $h(n - m K_G) e^{-j 2 \pi k_G n}$. However in this paper, in order to reduce the interference to OFDM signal and to match the definition in generating OFDM signal, Eq. (3) is used as defined in [4].

![System model and symbol configuration.](image)

2.2 Interference analysis

The interference from $s_{kG,m}$ for the target OFDM symbol can be evaluated by calculating the cross-correlation between $s_{kG,m}$ and the OFDM symbol. Let the correlation be noted as $c(m, \Delta k_F)$, where $\Delta k_F$ is the subcarrier interval defined as $\Delta k_F = N_F k_G / N_G - k_F$. The metric $c(m, \Delta k_F)$ is derived as follows.

$$c(m, \Delta k_F) = \sum_{i=0}^{N_F-1} g(i + \Delta n) e^{-j 2 \pi \frac{\Delta k_F}{N_G}} = \sum_{i=0}^{N_F-1} h(i + \Delta n - m K_G) e^{j 2 \pi \frac{\Delta k_F}{N_G}}$$

$$= \sum_{i=0}^{N_F-1} \sum_{k=-k_0}^{k_0} H(k') e^{j 2 \pi \frac{\Delta k_F}{N_G}} e^{j 2 \pi \frac{\Delta k_F}{N_G} \frac{i (k + k_0) + \Delta k_F}{N_G}}$$

$$= e^{2 \pi \frac{\Delta k_F}{N_G} \frac{\Delta k_0}{N_G}} \sum_{k'=-k_0}^{k_0} H(k') e^{j 2 \pi \frac{\Delta k_F}{N_G} \frac{\Delta k_0}{N_G}}$$

where:
\[ H'(k') = H(k') \frac{\sin \left( \pi \left( \frac{N_F k'}{N_G} + \Delta k_F \right) \right)}{\sin \left( \pi \left( \frac{k'}{N_G} + \Delta k_F \right) \right)}. \] (5)

When \( |s_{k,G,m}| = 1 \), interference power \( I(\Delta k_F) \) from all \( M \) subsymbols of the GFDM subcarrier is as follows.

\[
I(\Delta k_F) = \sum_{m=0}^{M-1} |c(m, \Delta k_F)|^2 
= \sum_{k'=-k_0}^{k_0} H'(k') \sum_{k''=-k_0}^{k_0} H''(k'') e^{j2\pi \left( \Delta n + \frac{N_{c,F} k''}{N_0} \right)} e^{-j2\pi m \frac{N_F k''}{N_0}} \sum_{m=0}^{M-1} e^{-j2\pi m \frac{N_F k''}{N_0}} 
= M \sum_{k'=-k_0}^{k_0} |H'(k')|^2
\] (6)

Therefore, the interference is independent of the time difference between symbols, \( \Delta n \).

If \( \Delta k_F \) is an integer:

\[
I(\Delta k_F) = M \sum_{k'=-k_0}^{k_0} |H(k')|^2 \frac{\sin^2 \left( \pi \left( \frac{N_F k'}{N_G} \right) \right)}{\sin^2 \left( \pi \left( \frac{k'}{N_G} + \Delta k_F \right) \right)}. \] (7)

Considering \( k_0 \) as defined in Eq. (2), \( k_0/N_G \leq (1 + \alpha)/(2K_G) \ll 1 \) usually holds true. Assuming that \( \Delta k_F/N_F < 1 \), for \( \Delta k_F \) such that \( k_0/N_G \ll \Delta k_F/N_F \ll 1 \), the following approximation is derived:

\[
I(\Delta k_F) \approx M \left( \frac{N_F}{\pi \Delta k_F} \right)^2 \sum_{k'=-k_0}^{k_0} |H(k')|^2 \sin^2 \left( \pi \left( \frac{N_F k'}{N_G} \right) \right) \] (8)

This means that the interference decreases by square of subcarrier interval \( \Delta k_F^2 \).

### 3 Numerical examples with simulation

Table 1 shows evaluation parameters in this section. By computer simulation, EVM (error vector magnitude) of detected OFDM symbol and the BER (bit error rate) are evaluated. In the theoretical analysis, the average square of EVM is considered as Eq. (7). If the interference is considered as Gaussian noise, the BER can be expressed as in Eq. (9) where \( E_b/N_0 \) is the ratio of the received energy per bit to the density of AWGN power.

<table>
<thead>
<tr>
<th>Table 1. Evaluation parameters</th>
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<tbody>
<tr>
<td>modulation</td>
</tr>
<tr>
<td>( N_F )</td>
</tr>
<tr>
<td>( K_G )</td>
</tr>
<tr>
<td>( M )</td>
</tr>
<tr>
<td>( \Delta n )</td>
</tr>
</tbody>
</table>
Results are shown in Fig. 2, which indicate the computer simulation agrees the analysis in Section 2.2. Note that a slight difference in BER performance is seen between simulation and analysis results in Fig. 2(b). The reason can be that the interference from the GFDM signal with QPSK modulation cannot be regarded as Gaussian noise exactly.

![Graph showing average square of EVM and BER performance](image)

(a) Average square of EVM as a function of $L$ representing time difference $\Delta \tau$.

(b) BER performance of OFDM transmission interfered by GFDM signal.

Fig. 2. Numerical results comparison.

### 4 Conclusions

This paper focused on GFDM coexisting with OFDM signal for migration scenarios from 4G to 5G mobile system, and theoretically analyzed the interference from the GFDM signal to the standard OFDM receiver. It has been shown that the analytical interference formula agrees well to the simulation results. Through this
work, the following properties have been pointed out. (1) Although some references adopt DFT at the GFDM generator, IDFT should be used to suppress the interference. (2) The interference is independent of the time difference between GFDM and OFDM symbols, which means that the cross-correlation does not change in multipath channel. (3) Approximately, the interference decreases by square of the subcarrier interval between the GFDM and OFDM symbols.

The analytical expression that is derived in this paper can be used not only for the interference evaluation in various symbol configurations, but also for some filter design purposes such as to reduce the cross correlation.

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DOA measurements using synthetic aperture method

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Abstract: It is important to understand the DOA characteristics in order to develop massive-array antennas for 5th generation mobile communication systems. We introduce a simple but effective method for measuring direction of arrival (DOA) that combines synthetic aperture (SA) processing with a receiving-system that consists of a turntable, vector receiver, and horn antenna. This report shows by simulation the effectiveness of synthetic aperture processing. The validity of this method is clarified by measurements in a chamber.

Keywords: synthetic aperture (SA), direction of arrival (DOA) measurement, antenna, propagation

Classification: Antennas and Propagation

References


1 Introduction

Studies on 5th generation mobile communication systems using high frequency bands, 6 GHz or above, are active [1]. In order to solve the problem of the high propagation loss, massive-array antennas such as Massive MIMO are attracting attention. Develop such an antenna demands an understanding of the propagation characteristics as the antennas have narrow beam characteristics. Therefore, a number of studies have described direction of arrival (DOA) measurements. There are 2 approaches to DOA measurements. The first uses a large scale aperture antenna such as a parabolic antenna or horn antenna with channel sounding system [2]. However, the antenna and channel sounding system must be redesigned when the measurement frequency is changed. The second uses just a few antenna elements with a high resolution estimation algorithm such as MUSIC, ESPRIT [3, 4, 5]. However, this demands calibration between each antenna. We combine the synthetic aperture technique [6] with a receiving-system consisting of a turntable, vector receiver, and horn antenna, to achieve higher angular resolution than the former approach and easier measurements than the latter. Amplitude and phase characteristics are obtained within the range of −180 degrees to 180 degrees as the receiving antenna is placed on a turntable R [cm] from the center, and obtained data is subjected to off-line synthetic aperture (SA) processing. Hence, the proposed method offers DOA measurements with high angular resolution by constructing a virtual circular arc antenna. It is possible to use a broadband receiving antenna without preparing an array antenna for each frequency, so this proposal offers wideband propagation characteristics and high versatility. In this report, we confirm the effectiveness of SA processing by simulation. In addition, its usefulness is verified by experiments in a chamber.

2 Measurement principle and measurement parameters

The proposal improves the DOA angular resolution by constructing a virtual circular arc synthetic aperture array antenna with radius of R. Assuming that the wave source (Tx) lies in the far-field, the measurement principle of this method is shown in Fig. 1(a). The receiver antenna (Rx) is placed R [cm] from the center of the turntable, and the transmission characteristics between receiver antenna (Rx) and wave source (Tx) are measured while the turntable is rotated from −180 degrees to 180 degrees. Array weights corresponding to the optical path difference are needed for constructing the virtual circular arc array antenna. The synthetic aperture array antenna is formed according to (1) by using measured electric fields and array weights.

\[ E_{SA} (\theta_i) = \sum_{j=-N}^{N} E(\theta_i + \phi_j) \cdot \exp\{j k R (1 - \cos(\phi_j))\} \]  

\( E_{SA} (\phi_j), E(\theta_i + \phi_j), \phi_j, \theta_i \) and \( \exp\{j k R (1 - \cos(\phi_j))\} \) are the synthesized electric field, the measured electric field, the setting angle of the j’th virtual antenna, the rotation angle, and the array weight, respectively. \( 2N + 1 \) receiver antennas (Rx) are formed at intervals of one degree. \( 2N + 1 \) Rx at \( \theta_i = 0 \) degrees is the real receiver antenna, \( 2N \) of \( 2N + 1 \) is the virtual antenna. The response from Rx is...
captured by the vector receiver, and then synthesized numerically in a PC in an offline manner.

Simulation and measurement parameters are shown Fig. 1(b). The receiving antenna is a horn antenna. Radiation pattern of the horn antenna assumed in the simulation is given by eq. (2). It is set to match the 3 dB beam-width of the horn antenna used in actual measurements.

$$E(\theta, \phi) = \frac{1 + \cos \theta}{2} \cdot \frac{\cos \left( \frac{\pi}{2} \cdot 1.15\lambda \right)}{1 - (1.15\lambda)^2} \cdot e^{-jkR(1-\cos \theta)}$$  \hspace{1cm} (2)$$

![Diagram](image_url)

(a): Measurement Principle
(b): Measurement and simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td>12</td>
</tr>
<tr>
<td>Antenna Element (Rx)</td>
<td>Horn antenna</td>
</tr>
<tr>
<td>Radius of array [cm]</td>
<td>20 (8 A)</td>
</tr>
<tr>
<td>Wave source (Tx) direction</td>
<td>0</td>
</tr>
<tr>
<td>Angle step [deg.]</td>
<td>1</td>
</tr>
<tr>
<td>Number of elements (2N+1)</td>
<td>121</td>
</tr>
</tbody>
</table>

Fig. 1. Principle and parameters

3 DOA spectra by SA processing

DOA spectra with and without SA processing are shown in Fig. 2(a). They are normalized against their respective peak values. In this paper, 3 dB beam-widths are defined as 3 dB resolution, 10 dB beam-widths are defined as 10 dB resolution. From Fig. 2(a), (b), the 3 dB resolution is 42.9 degrees without SA processing, and 4.9 degrees with SA processing. This result shows that the angular resolution can be greatly enhanced by acquiring the propagation characteristics given the radius from the center of the turntable and performing the SA processing offline.
4 Measurements in a chamber

In order to confirm the usefulness of the proposed measurement method, we measure the DOA in chamber using a 12 GHz band horn antenna. In accordance with the measurement principle, it SA processing is performed offline after obtaining the radiation characteristics. Fig. 3(a) shows the DOA spectra (measured and simulated) when one wave source is placed on the 0 degree axis. From Fig. 3(a), the 3 dB resolution is 4.9 degrees (simulated) and the 5.3 degrees (measured), which agree well. However, unwanted side-lobes lie on the −10 degrees direction. They indicate the influence of the amplitude and phase patterns of the antenna used in the measurements and the influence of the error between the phase center of the antenna and the rotation center. We think that it is necessary to apply a window function to reduce these side-lobes.

Wave sources were placed in the chamber at 0 degree and −10 degree directions, and DOA measurements of 2 waves were conducted. This technique makes it possible to know the arrival angle accurately.
In this paper, we introduced a DOA measurement method that uses a turntable, vector receiver, horn antenna and synthetic aperture processing; its usefulness was confirmed by simulation and measurements. This proposal greatly improves the angular resolution by forming a virtual array as the receiver set at a given radius processing the data off-line. Furthermore, by using a broadband antenna, it has the merit that various frequencies can be measured without changing the measurement system. In the future, delay wave measurements will be realized by this measurement method. In addition, we will conduct measurements in multipath environments and examine the measurement parameters.

5 Conclusions

In this paper, we introduced a DOA measurement method that uses a turntable, vector receiver, horn antenna and synthetic aperture processing; its usefulness was confirmed by simulation and measurements. This proposal greatly improves the angular resolution by forming a virtual array as the receiver set at a given radius processing the data offline. Furthermore, by using a broadband antenna, it has the merit that various frequencies can be measured without changing the measurement system. In the future, delay wave measurements will be realized by this measurement method. In addition, we will conduct measurements in multipath environments and examine the measurement parameters.

(b) Resolutions in Measurement

<table>
<thead>
<tr>
<th></th>
<th>Sim.</th>
<th>Mea.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 dB Res.</td>
<td>4.9</td>
<td>5.3</td>
</tr>
<tr>
<td>10 dB Res.</td>
<td>8.5</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of simulation and measurement results
Performance of throughput-based Q-routing

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Abstract: This paper proposes a scheme to reduce an initial learning period of Q-routing. Q-routing is a routing scheme to guide a packet on the fastest route. A neighbor node with the lowest $Q$ value, which is determined by a remaining time to the destination, is selected to send the packet. Before the routing is stable, the node learns the $Q$ value at the initial period. The Q-routing performs well in only a high traffic network, compared to a shortest path routing scheme. The proposed scheme reduces the initial learning period of Q-routing by considering a throughput of the node.

Keywords: Q-routing, traffic load, routing scheme

Classification: Network

References


1 Introduction

The information is transmitted in a network as data packets. Each packet travels from a source to a destination via transit nodes in a network. A traveling path of the packet is determined by a routing scheme.

A shortest path routing scheme considers the minimum total link cost along the path between the source and the destination. Either a transmission time on a link, number of hops, or link capacity is considered as the link cost. One of the possible paths that has the lowest cost is selected for the transmission. Some link is popular to be served for several source and destination pairs since its link cost is low. As a result, the communication via that link will be congested. Moreover, the processor
of the nodes that connect to the link may be overloaded due to the processing of the packet headers. Packets have to be queued in the nodes for the processing. As a result, the packets may take time to reach the destination. In this case, it would be better if the packets are transmitted to the other appropriate path to avoid the congestion.

Q-routing is a routing scheme to select a neighbor node with the shortest time to deliver a packet to the destination [1, 2, 3]. It considers the minimum $Q$ value, which is obtained by time to send a packet to the destination. The $Q$ value at each node is updated, using the information from replied message of a neighbor node on the path, every time a packet is sent. Q-routing has been adopted in wireless sensor networks for healthcare monitoring to lower the communication overhead [4].

The performance of both shortest path routing and Q-routing schemes were compared in [1]. In a network with low traffic load, an average delivery time of the shortest path routing scheme is low, while the Q-routing performs as well as the shortest path routing scheme after an initial learning period. In a network with high traffic load, the shortest path routing scheme no longer endures the packet load due to the congestion of the popular link. The Q-routing then outperforms the shortest path routing scheme. The traffic load in the network fluctuates. For example, the traffic load in a network in a resident area is high in the morning and evening, and it is low during a business hour. One of the routing schemes cannot achieve a good performance in every traffic situation. Sending the packet through a path with low congestion can reduce the delivery time since a queue for packet processing in each node is short.

In this paper, a routing scheme to reduce the initial learning period using throughput history is proposed, called a throughput-based Q-routing (TQ) scheme. The proposed TQ scheme modifies the updating process for $Q$ value of the Q-routing scheme. In the updating process, the TQ scheme considers throughput of a local node, instead of considering the time spending in a queue at the local node and time to transmit the packet to a neighbor node. Simulation result shows that the initial learning period in the TQ scheme is reduced, compared to the Q-routing scheme.

2 Q-routing scheme

The Q-routing scheme determines a path based on a remaining time to reach the destination. At the initial stage, a node randomly selects a path for a packet. Once the packet is transmitted, the node learns a travelling time of the selected path. The node makes an adjustment to select a path who has the shortest travelling time. After the learning period, a path with the shortest time to the destination is obtained.

A packet is sent from a source node $s$ to a destination node $d$. $x$ is an intermediate node along the path between $s$ and $d$. Let $y$ be one of the neighbor nodes of $x$. Let $Q_x(d, y)$ be a delivery time to send a packet from node $x$ to node $d$ via node $y$, including queuing time at node $x$, $q_x$, and a transmission time between nodes $x$ and $y$, $s_{xy}$. After the packet arrives at node $y$, node $y$ replies a remaining time on the path, $t$, to node $x$, where
Once node $x$ receives the response from node $y$, $Q_x(d, y)$ is updated as

$$Q_x(d, y) = Q_x(d, y) + \frac{\eta}{C} (q_x + s_{xy} + t - Q_x(d, y)),$$

where $\eta$ is a learning rate.

Fig. 1 shows an example of the Q-routing scheme. Node $x$ receives an updated information of $Q$ value from its neighbor nodes $y_1$ and $y_2$. It is assumed that the current $Q_x(d, y_1) = 2$, $Q_x(d, y_2) = 3$, and $\eta = 0.5$. A queuing time at node $x$ is assumed to be 5 ms. The transmission time between nodes $x$ and each neighbor node is 1 ms, $s_{xy_1} = s_{xy_2} = 1$ ms. The updated $Q_x(d, y_1)$ and $Q_x(d, y_2)$ become 5 and 6, respectively. Since $Q$ value of $Q_x(d, y_1)$ is less than $Q_x(d, y_2)$, the packet is sent from node $x$ to node $y_1$.

When a packet travels via a node with low throughput, it takes time to get an update from its neighbor nodes. As a result, a time for the learning period is long.

### 3 Proposed TQ scheme

The TQ scheme enhances the Q-routing scheme by considering throughput, instead of remaining time to a destination. The value of $Q$ is modified as,

$$Q_x(d, y) = Q_x(d, y) + \frac{\eta}{C} (a + t - Q_x(d, y)),$$

where $a$ is the number of packets that were forwarded from the local node to neighbor nodes within a given period of time. There are two policies to define $a$, non-indicated direction (ND) and indicated direction (ID).

#### 3.1 Non-indicated direction policy

In the ND policy, a throughput of node $x$ is defined by the number of forwarded packets considering the aggregated number of packets sent out from node $x$ to all the neighbor nodes. Fig. 2(a) shows an example of $Q$ value in the TQ scheme with ND policy. Node $x$ receives an updated information of throughputs from its neighbor nodes $y_1$ and $y_2$. The values of $Q_x(d, y_1)$, $Q_x(d, y_2)$, and $\eta$ are the same as in Fig. 1. A period of time to count the number of sent packets is set to five. This example shows the calculation of $Q$ values from 17th to 21st units of time. Five packets are sent out from node $x$ during the counting period. Updated $Q_x(d, y_1)$ and $Q_x(d, y_2)$ are

$$Q_x(d, y_1) = 2 + 0.5(5 + 1 + 2 - 2) = 5$$

$$Q_x(d, y_2) = 3 + 0.5(5 + 1 + 3 - 3) = 6$$
4.5 and 5.5 respectively. Since \( Q_x(d, y_1) \) is less than \( Q_x(d, y_2) \), the packet is sent to node \( y_1 \).

### 3.2 Indicated direction policy

In the ID policy, a throughput of node \( x \) is defined by the number of forwarded packets considering a direction of neighbor node. Fig. 2(b) shows an example of \( Q \) value in the TQ scheme with ID policy. Node \( x \) considers a throughput to each neighbor node. There are two and three packets sent out from node \( x \) to nodes \( y_1 \) and \( y_2 \), respectively, during the counting period. Updated \( Q_x(d, y_1) \) and \( Q_x(d, y_2) \) are 3 and 4.5, respectively. Since \( Q_x(d, y_1) \) is less than \( Q_x(d, y_2) \), the packet is sent to node \( y_1 \).

### 4 Performance and evaluation

The performance of the proposed scheme is evaluated via simulation using a topology in Fig. 3(a). The pairs of source and destination are randomly generated. The TQ scheme is compared to the conventional Q-routing scheme. In the simulation, we define a step as a packet forwarding stage for both queuing and transmitting. We take ten steps of the throughput from the history. The average number of generated packets per step at each node is set to two. Percentage difference of each scheme/policies is defined by a percentage difference value, which is calculated by \( \frac{|V_i - V_{i+1}|}{(V_i + V_{i+1})/2} \times 100 \), where \( V_i \) is the average.
number of steps for delivery at $i$th simulation step. The last simulation step that has the percentage difference value less than the given value is considered as a saturated point. In the evaluation, we set the percentage difference value to 2%.

Considering the number of simulation steps, Fig. 3(b) shows that the TQ scheme with both ND and ID policies have shorter simulation steps to achieve the saturated average number of steps for delivery than that of the Q-routing scheme. The Q-routing scheme takes 14,400 simulation steps. The TQ scheme with both ND and ID policies achieve the same result of 7,250 simulation steps, which is 50% reduction compared to the Q-routing scheme.

5 Conclusion

A scheme to reduce the initial learning period of the Q-routing scheme, called a throughput-based Q-routing (TQ) scheme, was proposed. The TQ scheme considers a throughput of neighbor nodes instead of remaining time to the destination. Packets are sent a neighbor node with low throughput to avoid congestion. Two policies, non-indicated direction (ND) and indicated direction (ID) policies, were introduced. The ND policy considers the aggregated number of packets that were sent out. The ID policy considers the number of packets that was sent to each neighbor node. Simulation result confirmed the reduction of the initial learning period of the proposed TQ scheme with both ND and ID policies.