Real-time road traffic awareness model based on optimal multi-channel self-organized time division multiple access algorithm

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ABSTRACT

Real-time road traffic awareness is a challenge in an intelligent transportation system or internet of vehicles. In this paper, we provide a real-time road traffic awareness model for vehicle drivers based on the optimal multi-channel self-organized time division multiple access algorithm. A system based on this model can be implemented in all kinds of road networks including urban and rural roads or highways and cover a large area. The results indicate that this system can identify more than 5000 vehicles within an identification radius of 40 km on rural roads or highways and more than 8000 vehicles within an identification radius of 8 km on urban roads. Simulation results show that a system based on this model can meet the drivers’ requirement of obtaining road traffic status in real time.

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1. Introduction

In recent decades, as a large number of vehicles ply on rural, urban, and metropolitan roads, an increasing number of people suffer from consequences such as traffic congestions, environment pollution, and economical losses [1]. Drivers experience stress during prolonged traffic jams; hence, it is especially important for them to be aware of the real-time road traffic status of area around them. Several solutions were provided for this purpose.

The first type of solution is derived from traditional intelligent traffic systems such as a video road traffic monitoring system and SAR (synthetic aperture radar)–based traffic monitoring system. The video road traffic monitoring system is a popular system [2,3] that is widely deployed on urban streets as well as highways. Video-based road traffic monitoring systems detect traffic through video image processing, modelling, and tracking techniques [4–6]. Reference [7] presented a real-time road traffic monitoring system based on the SAR system, which performs an aerial scan of the monitored area, processes the collected data, and distributes the traffic information through the traffic management centre.

The Internet of Vehicles (IoV), an important branch of the Internet of Things [8,9], is another popular solution for road traffic monitoring. Vehicular ad-hoc networks (VANETs) are an example of IoV, which works on a frequency of 5.9 GHz and has a coverage range of approximately 300 m [10]. A road traffic monitoring system based on VANETs collects the vehicles’ position through roadside access points and processes and analyses the road traffic information. Then, this information is distributed through websites, roadside bulletin boards, or other services accessible to the users [11–15]. Road traffic congestion can be forecast and controlled using this vehicle to vehicle communication along with the necessary infrastructure.

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http://dx.doi.org/10.1016/j.compeleceng.2016.07.004
0045-7906/© 2016 Published by Elsevier Ltd.

Please cite this article as: Q. Hu, L. Xu, Real-time road traffic awareness model based on optimal multi-channel self-organized time division multiple access algorithm, Computers and Electrical Engineering (2016),
http://dx.doi.org/10.1016/j.compeleceng.2016.07.004
Others, such as [16,17] presented a road traffic monitoring system that uses smart phones in collaboration with web services or centre services to show the road traffic status within the coverage area of wireless cellular networks.

However, all of the above solutions for road traffic monitoring require a significant amount of roadside infrastructure and data processing centres to inform the drivers about the road conditions. Otherwise, the process of obtaining the road traffic status for drivers may be delayed, and they may already be stuck in traffic at the time they get the information. Furthermore, these solutions cannot work in remote areas because it is impossible to deploy vehicle sensors everywhere.

In this paper, we present a real-time road traffic awareness model based on the optimal multi-channel self-organized time division multiple access (OMC-SOTDMA) algorithm. This model can be considered as a novel mode of the IoV. Utilizing this model, drivers can obtain quasi-real-time road traffic conditions in any area without relying on any other infrastructure except vehicle-to-vehicle communication terminals. When these communication terminals work on an appropriate frequency (such as a very high frequency, ultra high frequency, etc.) with the proper modulation method, they can cover a sufficient area with a single hop. Moreover, the technical architecture of this road traffic model is simpler and cheaper than that of the above-mentioned method.

The remainder of this paper is organized as follows. Section 2 describes the OMC-SOTDMA algorithm, Section 3 presents the identification area road model, Section 4 analyses the time slot collision and identification capability of the real-time road traffic awareness model based on the OMC-SOTDMA, Section 5 gives the numerical and simulation results, followed by the conclusion.

2. Optimal multi-channel-self organized time division multiple access (OMC-SOTDMA) algorithm

Slot selection method and slot self-organization are designed in the basic SOTDMA algorithm [18]. In order to enhance the related system capability, OMC-SOTDMA algorithm is applied to the real-time traffic awareness model; and both channel self-organization and slot self-organization need to be designed.

2.1. Notations

We assume that there are \( C_{n} \) channels, and every channel separates \( K \) time slots in one frame time \( T \). Let us denote the time slots of all the channels \( C_{n} \) by \( S_{k}^{i} \), \( S_{k}^{i} \) denotes the \( k \)th time slot of the \( C_{i} \) channel (see Fig. 1).

\[
S_{k}^{i} = \sum_{i=1}^{C_{n}} \sum_{k=1}^{K} S_{k} = C_{n} \cdot K. \quad (1)
\]

When identifying a vehicle running on the road, some time slots have to be used for sending its data packets. Here, \( R_{j} \) denotes data packet rate of the vehicle \( N_{j} \). In a frame time \( T \), the vehicle’s reserve slot number is given by:

\[
SN_{rsv, j} = T/R_{j}. \quad (2)
\]

We design the vehicle-identification data packet to occupy only one time slot for convenience in simulation.

2.2. Optimized multi-channel SOTDMA algorithm model

According to the notations above and the basic theory of SOTDMA [18], the optimal model of multi-channel SOTDMA algorithm is as follows:

1. Before sending the first packet, the vehicle has to listen for a frame time \( T \) to obtain the occupied slots map for all channels.
2. According to \( R_{j} \), there are nominal increment slots \( S_{N} \).
3. Select the first sending channel \( C_{i} \) by the random algorithm, and select the subsequent sending channels one at a time, unless there is no available slot. In this case, jump to choose the available channel.

\[
C_{i} = \begin{cases} 
\text{Random}(C_{n}) & \text{First} \\
\text{MOD}(C_{i+j}, C_{n}) & \text{Following}
\end{cases} \quad (3)
\]
(4) Randomly select the first nominal slot $S_{k} = \text{Random}(K', C_i)$, i.e., select a slot from the current slot to the $K'$ slot in the $C_i$ channel. Then, select the nominal slots ($S_{N}$) in every other $S_{N}$. 

(5) Calculate slots’ selection interval ($S_{SI}$) based on the $\lambda$ factor; $\lambda$ is a constant value corresponding to every $S_{NI}$. In addition, randomly select the transmission slot $S_{k}'$ within $S_{SI}$.

$$S_{k}' = \begin{cases} S_{FN} \pm \text{Random}(S_{SI}/2) & \text{First Select} \\ S_{k-1}' + S_{NI} \pm \text{Random}(S_{SI}/2) & \text{Following Select} \end{cases}$$

Here, $\pm \text{Random}(S_{SI}/2)$ means $S_{FN}$ or $S_{k-1}' + S_{NI}$ in the middle of $S_{SI}$.

(6) If $S_{k}'$ cannot be selected use the above model within the current $S_{SI}$, jump $S_{NI}$ slots to the next $S_{SI}$, and re-select.

(7) The identification packet includes the next time reserved slot information, which can help other identified vehicles update the occupied slot map and decrease the slot collision probability.

Based on the above model, the OMC-SOTDMA algorithm is given as:

Algorithm OMC-SOTDMA

Initialization:
Set Channels Number:$C_n$,
Every Frame Slots Number:$K$,
$S_{NI} \in \{S_{NI,1}, S_{NI,2}, \ldots , S_{NI,n}\}$,
$S_{NI,i}$ decided by Vehicle Speed $V_f$,
Current Slot Number: $S_{current}$
First Frame Flag:$bFlag = \text{FALSE}$;

Process:
1: if Listen Time $t \geq T$ $bFlag = \text{TRUE}$,
2: if $bFlag = \text{TRUE}$
3: $C_i = \text{Random}(C_n)$
4: $S_{FN} = \text{Random}(K', C_i)$
5: $S_{u} = S_k(S_{NI})$
6: $S_{j} = S_{FN} \pm \text{Random}(S_{SI}/2)$
7: Get Next Send Slot $\text{Fun}(C_i, S_{NI}, S_{u})$
8: Send First Packet
9: end if
10: while (TRUE) do
11: if ($S_{current} \neq S_{k}'$)
12: Get Next Send Slot $\text{Fun}(C_i, S_{NI}, S_{u})$
13: Send Packet
14: end if
15: end while
16: sub function: $\text{Fun}(C_i, S_{NI}, S_{u})$
17: $C'_i = \text{MOD}(C_i + C_u) (j = 1 \ldots C_n)$
18: $S_{j} = S_k(S_{NI})$
19: $S_{k}' = S_{k-1}' + S_{NI} \pm \text{Random}(S_{SI}/2)$
20: end sub

3. Identification area road model

3.1. Road net model

There are various road net structures [19], which can be classified into two types: the vast network urban road net and the long-line rural or highway road net.

Although there are various urban road nets, they can be simplified into a square road net model; the rural road or highway net can be simplified as a line road net model.

Based on the above models, a running vehicle has a regular identification area. An urban vehicle has to identify all the other vehicles around it while acquiring road traffic awareness whereas a rural vehicle only identifies the front and rear vehicles.

3.2. Assumptions and notations

To facilitate the calculation of the maximum number of vehicles in one vehicle identification area, some important assumptions and notations should be denoted.

(1) To simplify the analysis, we assume that the vehicles’ identification area is not circular but square with side length $2R(R)$ the identified radius, as in Fig. 2, especially in the case of urban road net.

(2) Another assumption is that we do not consider the road width, only number of lanes.

(3) There is only one-hop in the system based on OMC-SOTDMA when we select an appropriate frequency.
3.3. Vehicle safety distance

Maintaining a specific safe distance between running vehicles on the road, which is called the safety distance, is necessary in order to ensure the safety of vehicles. In general, the safety distance model is given as follows [20]:

\[ D_s = v_h(t_r + t_i/2) + \frac{v_h^2}{2\alpha_{max}} + d \]  

(5)

where \( D_s \) denotes the safety distance, \( v_h \) is the vehicle’s speed, \( t_r \) is the reaction time of the driver (approximately 0.8–1.0 s) [21], \( t_i \) is the deceleration time (approximately 0.1–0.2 s) [21], \( \alpha_{max} \) is the maximum deceleration (approximately 6–8 m/s) [21], and \( d \) is the minimum distance between vehicles when stopped (approximately 2–5 m) [20].

According to (5), on urban roads, when the vehicle’s speed is 70 km/h, the minimum safety distance is 50 m; on rural roads or highways, when the vehicle’s speed is 120 km/h, the minimum safety distance is 100 m.

3.4. Identification area vehicle numbers model

Based on the above, the maximum number of vehicles in one vehicle identification area is the sum of vehicles along the entire road length according to the minimum safety distance defined for a certain speed.

For the urban road net model, it is given as:

\[ M_U = \left( \sum_{j=1}^{H} \lambda_j \cdot 2R + \sum_{j=1}^{V} \lambda_j \cdot 2R \right) / D_s. \]  

(6)

For the rural road net model, it is given as:

\[ M_R = \lambda \cdot 2R/D_s. \]  

(7)
4. Real-time road traffic awareness model performance analysis

In a system based on the OMC-SOTDMA algorithm, a vehicle can perceive each time slot status and select one available time slot from a frame in order to transfer its message by the self-organized method. If there is no available time slot, it should increase its threshold to decrease its identification range. There may be two transmitters propagating their message for a receiver at the same time slot; this is called Slot Reuse [22–24]. In this case, the receiver may either not receive any message or only receive the stronger one; this leads to time-slot collision. In this section, we will analyse a vehicle identification capability based on the signal propagation theory.

4.1. Automatic signal detection threshold

When transmitted signal is in the wireless channel, the power along with some other factors can affect the radio wave propagation. In free space, the maximum distance between the transmitter and receiver can be calculated by the following equation:

\[ D_{m}^{2} = \frac{P_{T}G^{2}\lambda_{w}^{2}}{P_{R}16\pi^{2}}. \]  \( (8) \)

where \( D_{m} \) presents the maximum distance of radio wave propagation, \( P_{T} \) is the transmitter output power, \( P_{R} \) is the receiver required minimum power, \( G \) is the sum of transmit and receive gain, and \( \lambda_{w} \) is the radio wave length.

Based on (8), the maximum distance is determined from the minimum power required by the receiver. We can control the signal detection threshold of a receiver to get an appropriate distance. Obviously, there is a linear relationship between the receiver required power and the signal detection threshold.

\[ P_{R} = F(X_{Thr}) \]  \( (9) \)

As discussed above, when a vehicle can choose a free slot to broadcast its message based on OMC-SOTDMA, it can dynamically increase the detection threshold of the receiver, and the vehicle identification coverage is smaller than before. In practice, the following algorithm is proposed:

1. The minimum threshold \( X_{Thr}^{Min} \) is determined from the maximum distance. The maximum threshold \( X_{Thr}^{Max} \) is determined from the minimum required identification distance.
2. In general, when the free slots are below \( F_{Min}^{hr} \), the vehicle terminals increase the threshold \( X_{Thr} \) to \( X_{Thr}' = X_{Thr} + \Delta \), where \( \Delta \) is the minimum incremental threshold and \( X_{Thr}' \leq X_{Thr}^{Max} \).
3. Otherwise, when the free slots are above \( F_{Max}^{hr} \), the vehicles decrease the threshold \( X_{Thr} \) to \( X_{Thr}' = X_{Thr} - \Delta \), \( X_{Thr}' \geq X_{Thr}^{Min} \).

The variable \( X_{Thr} \) of the algorithm is adjusted to different scenarios automatically. It can affect the coverage of a vehicle and change the slot reuse topology, which leads to different slot collision probabilities and different identification capabilities.

4.2. Time-Slot collision and identification capability

In a system based on the OMC-SOTDMA, every vehicle can organize slot selection by itself, and there are no reused time slots in sight. However, a vehicle terminal can identify two or more vehicles not ‘in sight’ and probably reuse the same time slot to transmit identification information, which results in transmission conflict. Time slot collision is influenced by identification capability. We will now analyse time slot collision.

The successful reception of transmission by the vehicle depends on the power ratio of two transmitters. If all vehicles have the same nominal transmit power in the system, the power ratio can be converted to a distance ratio as:

\[ P_{r} = 20\log(D_{r}) \]

\[ D_{r} = \sqrt{10^{(P_{r}/10)}}. \]  \( (10) \)

Here, \( P_{r} \) is power ratio expressed in dB and \( D_{r} \) is the ratio of the distance between the two transmitters.

Based on the OMC-SOTDMA algorithm and (10), the time-slot collision probability is analysed as:

1) While \( D_{r} > 2 \), the power ratio is greater than 6 dB. This scenario is depicted in Fig. 3.

As Fig. 3 shows, the identification area of vehicle V is separated into three zones: A zone, B zone, and C zone. For the urban road model, we can separate the A and B zones into two parts each, namely the A1 and A2 zones, and the B1 and B2 zones. In the A1 zone, the vehicles on one side cannot identify those on the opposite side, but they can identify vehicles in the opposite B2 zone. Similarly, the vehicles in A2 zone cannot also identify those on the opposite side, but they can identify the vehicles in opposite B2 zone. The difference between B1 and B2 zone is also similar with A1 and A2 zone.

As mentioned above, in the A zones, the vehicle cannot identify vehicles on the opposite side, but they can be identified by the vehicle V. The time slot of the A zone vehicles on one side may be reused by vehicles on the opposite side of the A
zone only, and vice versa. In this case, all of them cannot be received by \( V \). Thus, the identification capability of \( V \) is affected by the time-slot collision.

It is assumed that vehicle distribution along the road lane is uniform. We assume that time slot selection is mutually exclusive in OMC-SOTDMA, and channel, slot interval, and time slot are selected randomly. In this case, time slot selection of the A zone vehicles is an independent probabilistic distribution event in the whole communication frame time slot, and the time-slot collision probability meets the Poisson distribution. The factor of Poisson distribution is \( k = 1 \) when there is only one hop. Thus, the time-slot collision probability of the rural road or highway model for the A zone is

\[
 p_{\text{Rural},A}^{D_t>2} = \left( \frac{M_R}{4S_R^2 - 3M_R} e^{-\left(M_U/\left(4S_R^2 - 3M_R\right)\right)} \right)^2.
\]  

(11)

The collision probabilities of zones A1 and A2 for the urban road model are:

\[
 p_{\text{Urban},A_1}^{D_t>2} = \left( \frac{M_U}{4S_U^2 - 3M_U} e^{-\left(M_U/\left(4S_U^2 - 3M_U\right)\right)} \right)^2
\]  

(12)

and

\[
 p_{\text{Urban},A_2}^{D_t>2} = \left( \frac{M_U}{8S_U^2 - 7M_U} e^{-\left(M_U/\left(8S_U^2 - 7M_U\right)\right)} \right)^2.
\]  

(13)

Vehicles in the B zone can identify each other. However, they cannot identify the opposite A zone vehicles. From (11), we can deduce the B zone time-slot collision probability of the rural road model as follows:

\[
 p_{\text{Rural},B}^{D_t>2} = \left( \frac{(D_t - 2)M_R}{D_t(4S_R^2 - 3M_R)} e^{-\left(M_U/(D_t(4S_R^2 - 3M_R))\right)} \right) \left( \frac{M_R}{4S_R^2 - 3M_R} e^{-\left(M_U/\left(4S_R^2 - 3M_R\right)\right)} \right).
\]  

(14)

Similar to the A zone in the urban road model, the B zone is also separated into sub-zones, B1 and B2. Their collision probabilities are:

\[
 p_{\text{Urban},B_1}^{D_t>2} = \left( \frac{(D_t - 2)M_U}{D_t(8S_U^2 - 6M_U)} e^{-\left(D_t(8S_U^2 - 6M_U)/D_t\right)} \right) \left( \frac{M_U}{4S_U^2 - 3M_U} e^{-\left(M_U/\left(4S_U^2 - 3M_U\right)\right)} \right)
\]  

(15)

and

\[
 p_{\text{Urban},B_2}^{D_t>2} = \left( \frac{(D_t - 2)M_U}{D_t(4S_U^2 - 3M_U)} e^{-\left(M_U/(4S_U^2 - 3M_U)\right)} \right) \left( \frac{M_U}{4S_U^2 - 3M_U} e^{-\left(M_U/\left(4S_U^2 - 3M_U\right)\right)} \right).
\]  

(16)

Synthesizing formulas (1), (6), (7), (11)-(16), the identification capability of the rural road model can be defined as:

\[
 C_{PD_t>2}^{\text{Rural}} = M_R \left( 1 - \left( \frac{p_{\text{Rural},A}^{D_t>2}}{D_t} + \frac{p_{\text{Rural},B}^{D_t>2}}{D_t} \right) \cdot \frac{D_t - 2}{D_t} \right).
\]  

(17)
Otherwise, the urban road model identification capability equation is as follows:

\[
C_{p^{Urban}}_{\text{rural}} = M_U \left( 1 - \left( p_{Urban,A1}^{rural} \cdot \frac{1}{4} + p_{Urban,A2}^{rural} \cdot \frac{1}{8} + \frac{D_r - 2}{4D_r^2} \cdot \frac{1}{2D_r} \right) \right). \tag{18}
\]

2) In Fig. 4, \( 1 < D_r \leq 2 \), and the power ratio is 0 to 6 dB.

When \( 1 < D_r \leq 2 \), there are also three zones: the A, B, and C zones. Like 1), the time slot selection of the A zone vehicles may conflict with those of the opposite sides. Although the vehicles of the B zone can reuse the same time slot as the vehicles on the opposite side in the A zone, they can also be received by the vehicle V. The time-slot collision exists only between the vehicles of the A zone.

As discussed above, for the rural road model, the time-slot collision probability of the A zone is:

\[
p_{rural}^{\text{rural}}_{\text{rural}} = \frac{(D_r - 1)M_R}{2D_rS_R^C} \frac{2 + (D_r - 1)M_R}{(D_r - 1)M_R} e^{\frac{(D_r - 1)M_R}{2D_rS_R^C}} - 1 \tag{19}
\]

As discussed above 1), the urban road model can be separated into the A1 zone and A2 zone. Their probabilities are

\[
p_{Urban,A1}^{rural} = \frac{(D_r - 1)M_U}{2D_rS_R^C} \frac{2 + (D_r - 1)M_U}{(D_r - 1)M_U} e^{\frac{(D_r - 1)M_U}{2D_rS_R^C}} - 1 \tag{20}
\]

and

\[
p_{Urban,A2}^{rural} = \frac{(D_r - 1)M_U}{2D_rS_R^C} \frac{2 + (D_r - 1)M_U}{(D_r - 1)M_U} e^{\frac{(D_r - 1)M_U}{2D_rS_R^C}} - 1 \tag{21}
\]

Similar to (17), the identification capability of a rural road model is given by (22).

\[
C_{p^{rural}}^{rural} = M_R \left( 1 - \left( p_{rural,A1}^{rural} \cdot \frac{1}{4} + p_{rural,A2}^{rural} \cdot \frac{1}{8} + \frac{D_r - 2}{4D_r^2} \cdot \frac{1}{2D_r} \right) \right) \tag{22}
\]

Furthermore, the identification capability of an urban road model is expressed by (23).

\[
C_{p^{Urban}}^{Urban} = M_U \left( 1 - \left( p_{Urban,A1}^{Urban} \cdot \frac{D_r - 1}{2D_r} + p_{Urban,A2}^{Urban} \cdot \frac{D_r - 1}{2D_r^2} \right) \right) \tag{23}
\]

5. Simulation and numerical results

In the simulated road model, we assumed four lanes in each road, with a road every 500 m, and vehicles moving at speeds from 0–100 km/h in urban areas. Similarly, we propose eight lanes and vehicle speed from 60–160 km/h on rural
roads or highways. We can illustrate the number of vehicles in different identification coverage (radius) and different vehicle speeds based on the assumption as shown in Figs. 5 and 6.

According to the American urban street level-of-service, a situation is classified as traffic congestion when the vehicles’ speeds are below 20 km/h [1]. Generally, it is impossible for a traffic congestion to cover the entire area. While discussing the identification time-slot collision and identification capability, we set the vehicle speed as 50 km/h on urban roads and 120 km/h on rural roads/highways. Under the circumstances, there are approximately 10,000 vehicles in an identification radius of 10 km, which means that the identification area coverage is 400 km² in an urban area, and approximately 3000 vehicles on rural roads/highways.

We assume that the communication system data rate is 38.4 kbps, every hardware link identification packet is 256 bits and 4 channels, and every frame’s time is 30 s; thus, we have 18,000 time slots. When the vehicle speed is less than 30 km/h, it transmits message once per frame time, twice between 30 km/h and 90 km/h, and thrice when the speed is more than 90 km/h. Then, different numbers of vehicles require different time slots and different time-slot collision ratios (see Fig. 7). The time-slot collision ratio of OMC-SOTDMA is less than that of single SOTDMA; however, there is a reduced tolerability. But it can be perfectly resolved by the signal detection threshold algorithm. Although the rural model has a higher collision ratio than the urban model, there are many more vehicles in the urban area within the same identification radius, as shown in Figs. 5 and 6. When 18,000 time slots are required, the time slot-collision ratio is 6.77% (see Fig. 7), which means that the vehicle can recognize about 93.23% time slots. Thus, we can implement a design such that the received signal detection...
threshold is changed when one vehicle has a free time slot ratio less than 90%, which is a sufficiently high identification ratio.

We obtain the identification capability and identify the number of vehicles in different identification radii by combining the above results. Fig. 8 shows the rural road or highway model when the vehicle speed is 120 km/h and identification radius is 40 km; the identification capabilities are 92.3% and 97.2% at distance ratios of 2.5 and 1.5, respectively. The numbers of identified vehicles are 5000 and 5300, respectively, which provides sufficient coverage of the surrounding vehicles for the driver to select the optimal route in real time. In the urban road model of Fig. 9, when the identification radius is 8 km and distance ratios are 2.5 and 1.5, the identification capabilities are 94.9% and 97.7%, respectively, and the numbers of identified vehicles are 8260 and 9500, respectively. These are also sufficient for a driver to know about the traffic environment in real time.

6. Conclusion

The real-time road traffic awareness model based on the OMC-SOTDMA algorithm is feasible and more efficient and fair compared with others, as illustrated above. It provides coverage of the traffic situation of a large area to the drivers, on urban and rural roads or highways. This real-time road traffic awareness method does not rely on any other centre services and roadside infrastructure, and can be used in any area. When the number of time slots required for the identified vehicles is greater than the number of slots provided, new vehicles cannot be accessed, but the situation can be perfectly resolved by adjusting the automatic signal detection threshold, as shown in Section 4.
Acknowledgments

This work was supported in part by the China National Science and Technology Infrastructure Program (no. 2012BAH36B02), The State Key Program of National Natural Science of China (no. 61231006).

References

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