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Hierarchical model of information signals formation at the physical layer in FANET

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ABSTRACT

Creation of reliable and efficient flying ad-hoc networks (FANET) requires detailed development of the model of the physical layer of data transmission, determined by the conditions of operation of the networks. The problems of well-known software simulators of communication networks are the simplified nature of the physical layer, as well as the inability to obtain specific analytical solutions in the process of simulation. The hierarchical model of formation of information signals which allows to represent various types of communication channels and the channel-forming equipment, for providing their analytical description and the further analysis is developed. The model allows to describe communication channels between UAVs and (or) ground control centers taking into account the effects of attenuation, intersymbol interference, multipath propagation of signals; schemes of terminal and intermediate network equipment with linear and nonlinear signal conversion; circuits with forward regulation, backward regulation and combined regulation; circuits with multi-channel signal generation and processing, as well as cross-links between channels. Analytical expressions of the transfer function of the generalized hierarchical model for an arbitrary number of disclosed levels of hierarchy are obtained. An example of the presentation and study of the UAV transmitter circuit on the basis of a hierarchical model of signal formation is considered.

KEYWORDS: unmanned aerial vehicles; FANET; physical layer; basic network; communication channel; hierarchical model.

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Modelo jerárquico de formación de señales de información en la capa física en FANET

RESUMEN

La creación de redes de vuelo ad-hoc confiables y eficientes (FANET) requiere un desarrollo detallado del modelo de la capa física de transmisión de datos, determinada por las condiciones de operación de las redes. Los problemas de los simuladores de software conocidos de las redes de comunicación son la naturaleza simplificada de la capa física, así como la incapacidad de obtener soluciones analíticas específicas en el proceso de simulación. Se desarrolla el modelo jerárquico de formación de señales de información que permite representar varios tipos de canales de comunicación y el equipo de formación de canales, para proporcionar su descripción analítica y el análisis posterior. El modelo permite describir canales de comunicación entre UAV y (o) centros de control en tierra teniendo en cuenta los efectos de atenuación, interferencia entre símbolos, propagación de señales por trayectos múltiples; esquemas de equipos de red terminales e intermedios con conversión de señal lineal y no lineal; circuitos con regulación hacia adelante, regulación hacia atrás y regulación combinada; circuitos con generación y procesamiento de señales multicanal, así como enlaces cruzados entre canales. Se obtienen expresiones analíticas de la función de transferencia del modelo jerárquico generalizado para un número arbitrario de niveles de jerarquía revelados. Se considera un ejemplo de la presentación y estudio del circuito transmisor UAV sobre la base de un modelo jerárquico de formación de señal.

PALABRAS CLAVE: vehículos aéreos no tripulados; FANET; capa física; red básica; canal de comunicación; modelo jerárquico.

Introduction

Flying ad-hoc networks (FANET), which are a kind of mobile ad-hoc networks (MANET), are used to solve a wide class of tasks based on unmanned aerial vehicles (UAVs): the organization of protection (Sun et al., 2011), signal relay between two networks (De Freitas et al., 2010; Jiang, 2010), monitoring of the natural environment (Cho et al, 2011; Xiang &Tian, 2011) and technical objects (Maza et al., 2011; Semsch et al., 2009), etc. The effectiveness of FANET largely depends on the organization of the physical layer. Creating a robust FANET data architecture requires a detailed model representation of the physical layer. At this layer, radio wave propagation models (Ahmed et al., 2011; Abualhaol & Matalgah, 2011) and antenna structures (Ramanathan, 2001; Noubir, 2004) are considered. The variation of a large number of heterogeneous factors (environmental conditions, radio signal reflection characteristics, natural and intentional interference, etc.) makes it difficult to create reliable models of network interaction in FANET at the physical layer. The modeling problem is further complicated by the extremely high mobility of nodes (Wang et al., 2010; Kuiper & Nadjm, 2006).

Currently, there are a number of specialized software simulators of computer networks, for example, OPNET, NS-2, NS-3, Omnet++, allowing to model the protocols of ad-hoc networks of different layers of the OSI model (from the lower physical to the upper application) (Abuarqoub et al., 2016). However, the problem with such software tools is the simplified nature of the physical layer. When using such simulators, it is difficult or impossible to reliably take into account factors such as the simultaneous influence of a large number of destabilizing perturbations in the simulation process. It is also problematic to carry out modeling considering the transfer functions of communication equipment, causing distortion of information signals due to various inertials and nonlinearities of the component blocks.

These problems determine the relevance of the analysis of communication networks and use of general-purpose software packages, such as MatLAB / Simulink (Gilat,2004). Due to the large number of built-in functions of digital and analog signal processing, this environment allows to explore a wide class of effects of the physical layer of wireless networks (the impact of noise with different spectra and distribution laws, the propagation of radio signals in the atmosphere and transmission paths). In (Qutaiba, 2012; Qutaiba et al., 2011), a simulation of a wireless sensor network using MatLAB/Simulink was performed, as a result of the simulation, the nature of signals at different noise levels was revealed. The disadvantage of this approach is the lack of general analytical solutions for varying the parameters of the channel or signal processing paths.

The aim of the work is to develop and apply a hierarchical model of information signals formation for numerical and analytical modeling of UAV networks at the physical layer.

1. Hierarchical model of information signals formation at physical layer

The hierarchical model of information signals formation should allow representation of various kinds of communication channels and the channel-forming equipment, for ensuring their analytical description and the further analysis. The generalized model should provide a representation of communication channels between UAVs and (or) ground control centers, taking into account the effects of attenuation, intersymbol interference, multipath propagation of signals. In addition, the model should allow the study of terminal and intermediate network equipment circuits with linear and nonlinear signal conversion; circuits with forward regulation (FR), backward regulation (BR) and combined regulation; circuits with multi-channel signal generation and processing, as well as with cross-links between channels.

To simplify the analysis, the construction of a hierarchical model should be carried out on the basis of a minimum number of similar blocks with possibility of their arbitrary increase. At the same time, the integrity of the general forward, backward and channel links must be maintained. The generalized model contains an arbitrary number of parallel, dependent channels - "lines" that form a "frame". It can be disclosed (unfolded) in a raster way on "lines" (disclosure on levels) and on "frame", with any lengths of "lines" and their quantity.

Each "line" of the scheme is a generalized transformer of signals (TS) of a certain level of disclosure (Fig. 1). The structure of the TS includes: similar to it TS, control unit (CU), control path (CP) and weighted summator (WS).

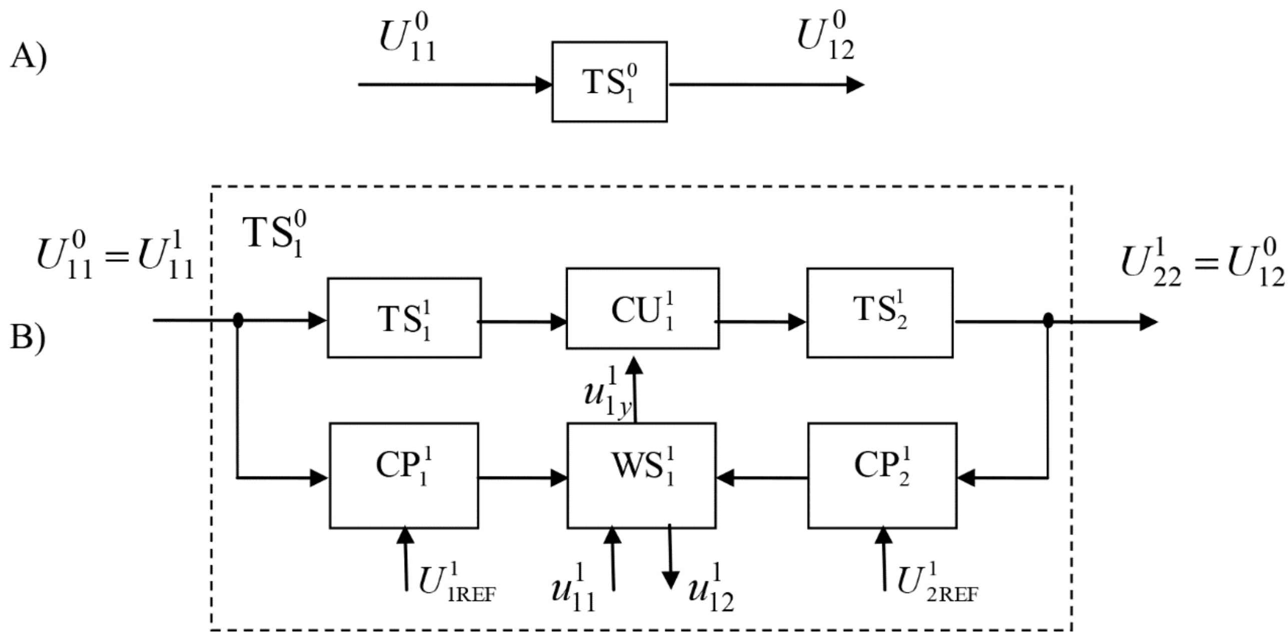

Figure 1. Structure of the generalized transformer of signals

The generalized signal generator contains two control circuits – FR and BR. Each CP generates a control signal and includes a series-connected detector (D) and a filter (F). As D, the model may contain amplitude, frequency or phase detectors, depending on the type of modulation used at the physical layer. The CU model describes the control of the amplitude, phase and (or) frequency of the signal. WS (Fig. 2) commutes signals. The WS coefficients determine the summation sign and the ratio of the signal transmission from the WS inputs to the WS outputs.

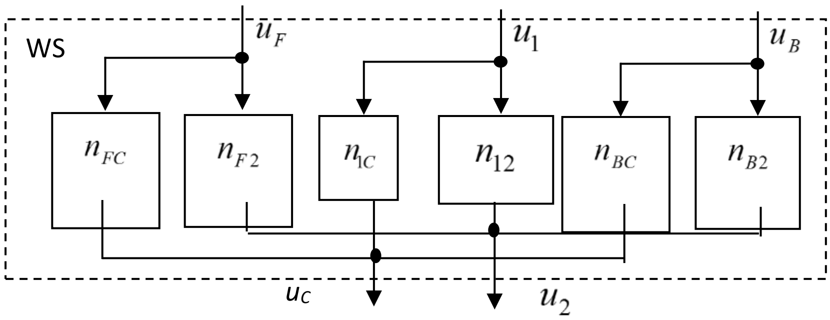

Figure 2. Model of the weight summation

The following designations of blocks are accepted on schemes: $TS^{x_1}_{x_2}$, where x1 is a level number, x2 is a block number. The *U* symbols denote the external main input and output signals, and the *u* symbols denote the auxiliary signals.

The upper and lower indices of the signals are denoted as $U^{y_1}_{y_2\,y_3}$, where y_1 is the level number, y_2 is the block number to which the signal belongs, y_3 is a signal identifier. The identifier y_3 can take the following alphabetical and numerical designations: 1 – input unit, 2 – output, *REF* – signal of the reference oscillator, *F* – forward regulation path, *B* – backward regulation path, *u* – CU control signal.

Figure 3 shows several hierarchical levels of disclosure of the TS model. Zero level (Fig. 1A) corresponds to a folded transformer. Level 1 (Fig. 1B) is the basic TS. Its further disclosure allows to arbitrarily increase the number of signal transformations in the "line" (channel). Each disclosure of the next level is carried out by the disclosure of the TS scheme (Fig. 1B) contained in the previous level.

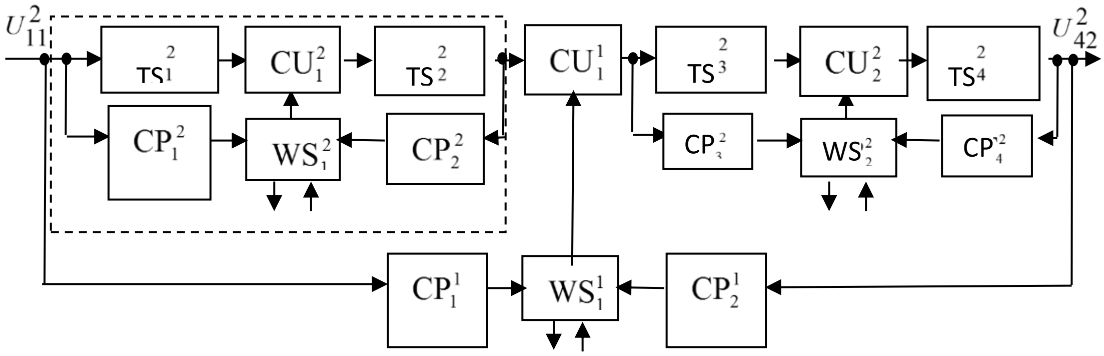

Figure 3. Unfolding of the transformer model

Let us denote the transfer functions of the blocks: TS→ П, CU → K, WD→ n, CP→ W. Let the upper and lower indices of the functions fully correspond to the upper and lower indices of their blocks. According to Fig. 1, Fig. 3 the TS transfer functions of different levels are obtained by multiplying the transfer functions of the constituent blocks and have the form

level 0 $Q^0 = \Pi_1^0$ – folded TS,

level 1 $Q^1 = \Pi_1^1 K_1^1 \Pi_2^1$,

level 2 $Q^2 = \Pi_1^2 K_1^2 \Pi_2^2 K_1^1 \Pi_3^2 K_2^2 \Pi_4^2$,

level 3 $Q^3 = \Pi_1^3 K_1^3 \Pi_2^3 K_1^2 \Pi_3^3 K_2^3 \Pi_4^3 K_1^1 \Pi_5^3 K_3^3 \Pi_5^3 K_3^3 \Pi_6^3 K_2^2 \Pi_7^3 K_4^3 \Pi_8^3$.

The general expression of the transfer function for an arbitrary number of disclosed levels $A \geq 1$

$$Q^A = \prod_{\alpha=1}^{A} \prod_{\beta=1}^{B} \prod_{\gamma=1}^{G} \Pi_\beta^\alpha K_\gamma^\alpha ,$$

where α is a current number of disclosed layer, *A* is the maximum number of layers disclosed in TS, β, γ are coefficients (number of transfer functions) of the TS and CU, respectively, *B*= 2^α, *G*= $2^{\alpha-1}$ are maximum values of β, γ.

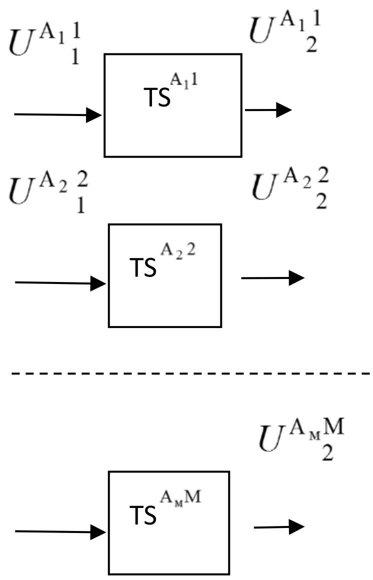

Figure 4. Parallel unfolding of the transformer model

A generalized model of signal formation containing M "strings" ("lines") is presented in Fig. 4. The upper right indices of blocks, signals and transfer functions correspond to the "line" number.

The totality of input and output signals denote through the matrices $\boldsymbol{U}^{A_M M}_{1,2}$, and through the matrix $\boldsymbol{Q}^{A_M M}$ - a set of transfer functions. Then the generalized model is described by a system of equations

$$\boldsymbol{U}^{A_M M}_2 = \boldsymbol{Q}^{A_M M} \boldsymbol{U}^{A_M M}_1 .$$

The principle of constructing a model based on raster signals formation allows us to reduce model-specific channel in the FANET or scheme specific device of channel-formation equipment to a transfer characteristics in the corresponding "frame" element of generalized hierarchical model.

2. Investigation of UAV transmitter circuit on the basis of hierarchical model of signal formation

Consider the UAV transmitter circuit with amplitude (phase) modulation and automatic gain control (AGC) (Fig. 5A), and its representation on the basis of a hierarchical model of signal formation (Fig.5B).

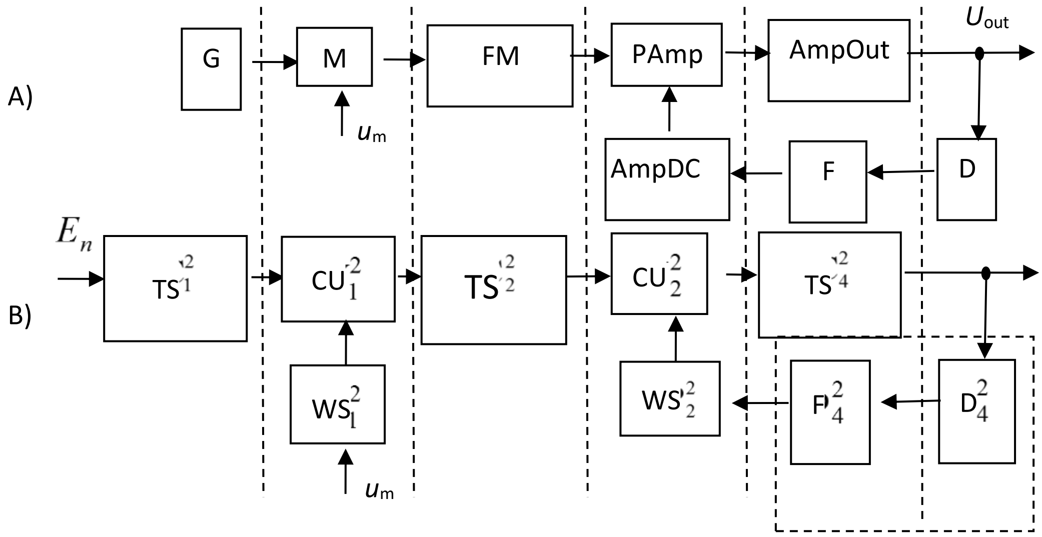

Figure 5. Block diagram of the UAV transmitter

Here the following designations are accepted:

G – transmitter generator, M – modulator, FM – frequency multiplier, PAmp – adjustable power amplifier, AmpOut – output power amplifier, D, F and AmpDC – detector, filter and DC amplifier of the AGC system, accordingly;

u_m – modulating signal, E_P – power supply voltage.

Let us also denote $U_G = U_m \cos \omega t$ – the output signal of the generator, U_m – amplitude, ω – carrier frequency, t – time;

K_M, K_{FM}, K_{PAmp}, K_{AmpOut}, D_A, M_A, n_A – transmission coefficients of modulator, frequency multiplier, adjustable and output power amplifiers, detector, filter and DC amplifier of AGC, respectively.

Then the transfer functions of the blocks of the generalized model:

$$\Pi_1^2 = (U_m / En)\cos \omega t,\ K_1^2 = K_M,\ \Pi_2^2 = K_{FM},\ K_2^2 = K_{PAmp},\ \Pi_4^2 = K_{AmpOut},\ K_1^1 = \Pi_3^2 = n_1^2 = 1,$$
$$W_1^1 = W_2^1 = W_1^2 = W_2^2 = W_3^2 = 0,\ D_4^2 = D_A,\ M_4^2 = M_A,\ n_{2BC}^2 = n_A.$$

Their substitution in the final transfer functions of the generalized scheme allows to immediately obtain expressions for dynamic, amplitude-frequency modulation and other characteristics of a particular transmitter. The submission required one "row" and two levels of TS disclosure. If necessary, the output of the model Fig. 5 can be added in series connected units, describing the transfer function of the communication channel and the transfer function of the input paths of the UAV receiver or control center. This approach can be used for analysis of a wide class of network equipment circuits with multi-channel signal generation and processing, as well as cross-links between channels.

Thus, the developed generalized hierarchical model and analysis methodology based on it can simplify the process and reduce the time spent on the study of specific channels or network equipment in UAV networks at the physical layer.

Conclusions

The effectiveness of FANET networks is highly dependent on the physical layer. A reliable description of the physical layer of the FANET requires the creation of an adequate model describing the radio signal propagation in the atmospheric communication channel, the formation and conversion of signals in the paths of the transmitter and receiver of the UAV or ground control center, signal conversion in the antenna system. Varying a large number of heterogeneous factors makes it difficult to create reliable models of network interaction in FANET at the physical layer. Serious disadvantages of many specialized and universal software simulators of communication networks are the simplified nature of the physical layer, as well as inability to obtain the necessary analytical solutions in the process of simulation.

The developed hierarchical model of information signals formation allows to consider various kinds of communication channels and channel-forming equipment, provide their analytical description and further analysis. Attenuation and intersymbol interference in the communication channel are taken into account in the model by the introduction of inertial frequency-dependent links, multipath propagation of signals - summation of signals on individual beams considering their time shifts. Due to the presence of frequency-dependent filtering units and nonlinear detection units, the model allows to study the schemes of terminal and intermediate network equipment with linear and nonlinear signal conversion. Due to the presence of forward and backward control circuits, the hierarchical model allows to describe a wide class of network equipment circuits with multi-channel signal generation and processing, as well as cross-links between channels.

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References

Abualhaol, I. Y.; Matalgah, M. M. (2011). Performance analysis of cooperative multi-carrier relay-based UAV networks over generalized fading channels, International Journal of Communication Systems 24 (8) (2011) 1049–1064.

Abuarqoub, A.; Hammoudeh, M.; Alfayez, F.; Aldabbas, O. (2016). A Survey on Wireless Sensor Networks Simulation Tools and Testbeds. In book: Sensors, Transducers, Signal Conditioning and Wireless Sensors Networks Advances in Sensors: Reviews, Vol. 3 Chapter: 14 Publisher: IFSA. 2016.

Ahmed, N.; Kanhere, S.; Jha, S. (2011). Link characterization for aerial wireless sensor networks, in: GLOBECOM Wi-UAV Workshop, 2011, pp. 1274–1279.

Cho, A.; Kim, J.; Lee, S.; Kee, C. (2011). Wind estimation and airspeed calibration using a UAV with a single-antenna GPS receiver and pitot tube, IEEE Transactions on Aerospace and Electronic Systems 47 (2011) 109–117.

De Freitas, E. P.; Heimfarth, T.; Netto, I. F.; Lino, C. O.; Pereira, C. E.; Ferreira, A. M.; Wagner, F. R.; Larsson, T. (2010). UAV relay network to support WSN connectivity, ICUMT, IEEE, 2010, pp. 309–314.

Gilat, A. (2004). MATLAB: An Introduction with Applications 2nd Edition. John Wiley & Sons. ISBN 978-0-471-69420-5.

Jiang, F.; Swindlehurst, A. L. (2010). Dynamic UAV relay positioning for the ground-to-air uplink, in: IEEE Globecom Workshops, 2010.

Kuiper, E.; Nadjm-Tehrani, S. (2006). Mobility models for UAV group reconnaissance applications, in: Proceedings of International Conference on Wireless and Mobile Communications, IEEE Computer Society, 2006, p. 33

Maza, I.; Caballero, F.; Capitán, J.; Martínez de Dios, J. R.; Ollero, A. (2011). Experimental results in multi-UAV coordination for disaster management and civil security applications, Journal of Intelligent and Robotics Systems 61 (1–4) (2011) 563–585.

Noubir, G. (2004). On connectivity in ad hoc networks under jamming using directional antennas and mobility, in: Wired/Wireless Internet Communications, Lecture Notes in Computer Science, vol. 2957, Springer, Berlin/Heidelberg, 2004, pp. 521–532.

Qutaiba, A. (2012). Simulation Framework of Wireless Sensor Network (WSN) Using MATLAB/SIMULINK Software. In book: MATLAB - A Fundamental Tool for Scientific Computing and Engineering Applications, 2012, Volume 2. 10.5772/46467.

Qutaiba, A.; Abdulmaowjod, A.; Hussein, M. (2011). Simulation & performance study of wireless sensor network (WSN) using MATLAB, Conference: Energy, Power and Control (EPC-IQ), 2010, pp. 307 - 314.

Ramanathan, R. (2001). On the performance of ad hoc networks with beamforming antennas, in: Proceedings of the 2nd ACM International Symposium on Mobile Ad Hoc Networking &Computing, MobiHoc '01, ACM, New York, NY, USA, 2001, pp. 95–105.

Semsch, E.; Jakob, M.; Pavlícek, D.; Pechoucek, M. (2009). Autonomous UAV Surveillance in Complex Urban Environments, in: Web Intelligence, 2009, pp. 82–85.

Sun, Z.; Wang, P.; Vuran, M. C.; Al-Rodhaan, M.; Al-Dhelaan, A.; Akyildiz, I. F. (2011). BorderSense: border patrol through advanced wireless sensor networks, Ad Hoc Networks 9 (3) (2011) 468–477.

Wang, W.; Guan, X.; Wang, B.; Wang, Y. (2010). A novel mobility model based on semi-random circular movement in mobile ad hoc networks, Information Science 180 (3) (2010) 399–413.

Xiang, H.; Tian, L. (2011). Development of a low-cost agricultural remote sensing system based on an autonomous unmanned aerial vehicle, Biosystems Engineering 108 (2) (2011) 174–190.